Renewable and Sustainable Energy Reviews 81 (2018) 2236–2263

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review of cogeneration system in a microgrid: A perspective from architecture and operating system

Normazlina Mat Isa, Chee Wei Tan*, A.H.M. Yatim

Department of Electrical Power Engineering, Faculty of Electrical Engineering, University Teknologi Malaysia, Johor 81310, Malaysia

ARTICLE INFO

Keywords:
Cogenerations
Prime movers
Hierarchical control
Fuel cell
Commercial building

ABSTRACT

Several factors such as climate change, increment in fuel cost and digital technology era have lead to transformation of conventional grid into smart grid. Existing microgrid can be integrated with smart grid characteristics by various topologies, including cogeneration system where both electricity and thermal energy from single source of fuel can be produced. Cogeneration system has better efficiency, lower costs and able to reduce greenhouse gas emissions compared to singular conventional methods. This paper presents a comprehensive review of cogeneration system, covering the principle operation and types of prime movers available for use in power plant, building and industrial plant. Prime movers such as gas turbine, steam turbine, micro turbine, reciprocate engine and fuel cell are compared in terms of size (kW), efficiency and principal operation. This review also describes the hierarchical control system for cogeneration system; classified into three types, which are local, centralized and decentralized. This study tries to find the most suitable control strategy for certain cogeneration system by referring to the related standards available. A number of cogeneration applications in commercial buildings, including hospital, airport, shopping complex and hotel, are presented to show the effectiveness of the cogeneration system. Overall, this paper presents comparison between each prime mover technology, factors that influence the selection of prime movers, challenges and prospects of cogeneration system.

1. Introduction

Integration of cogeneration system or combined heat and power (CHP) is not new because these technologies have been used in the industrial plants in the early 1880s when steam was the primary source of energy. Cogeneration is defined as energy generation unit that simultaneously produces both electricity and thermal from a single fuel source. Public Utility Regulatory Policies Act (PURPA) defines cogeneration as the production of electric energy and steam or forms of useful energy, such as heat, that can be used for industrial, commercial, heating or cooling purposes [1]. Meanwhile, World Alliance for Decentralization Energy defines cogeneration as a "process of producing both electricity and usable thermal energy (heating or cooling) at high efficiency and near the point of use" [2]. In current situation where power generation systems are facing substantial transformation from conventional electricity production to modern Smart Grid (SG), adaptation of cogeneration system undeniably more efficient and suitable in many cases of energy generation. Issues like climate changes, increment in fuel prices, and advancement of digital and communication technologies are the main factors that lead to more SG implementation [3]. In addition, global workforce has begun applying digital, computerized and communication technologies in their daily work, since the 21st century electricity delivery system involves consumers in electricity generation and power trading. Modern technologies in digital, computer and communication have urged people to be more alert in their power usage [4], since as customers of power system industry, they have the responsibility to better manage their grid, handle costly power outage, perform real time meter reading and have choices of dynamic power prices [5–9]. With regard to SG technologies, microgrids are developed with various topology combinations of energy sources, energy storages, power electronics devices and loads. Among all microgrid topologies, cogeneration system or combined heat and power (CHP) is the best mechanism that can help to achieve SG objectives.

Cogeneration is not new; industrial plants have used the cogenerations concept in early 1880s when steam was the primary source of energy. At that time, electricity had just emerged as a source for both power and lighting [10]. The use of cogeneration system became a common practice when the engineers utilized steam belt and pulley mechanism to produce electric power by motors; which is a transfor-

* Corresponding author.
E-mail addresses: mzzlina@gmail.com (N.M. Isa), cheewei@fke.utm.my (C.W. Tan), halim@fke.utm.my (A.H.M. Yatim).

http://dx.doi.org/10.1016/j.rser.2017.06.034
Received 20 February 2016; Received in revised form 4 June 2017; Accepted 9 June 2017
Available online 16 June 2017
1364-0321/

mation from mechanical powered system into an electrically powered system. In early 20th century, coal fired boilers and steam turbine generators were used to generate electricity, and the by-product, the exhaust steam, was used for industrial heating applications [11]. Implementation of cogeneration in power plant station declined in US by 1950s, accounting for only 15% of total electrical generation, and the further dropped to about 5% in 1974. This was due to the construction of central electric power plants and reliable utility grids, leading to the reduction in the cost of electricity. This influenced the industrial plants to buy electricity from utility companies and stop generating their own. Moreover, factors like increasing regulatory policies regarding electric generation, low fuel costs, advance boilers technologies and strict environmental control have led to the decline of cogeneration system [12]. Nevertheless, this downward trend started to revert after the first fuel crisis in 1973. Due to the increment in energy prices and uncertainty of fuel supply supplies, engineers started to find other alternatives to produce their electricity by using more efficient system that can utilize unconventional fuels like cogeneration. Cogeneration system are suitable for building applications, including hospitals, institutional buildings, hotels, office buildings and single- and multi-family residential buildings [13]. The applications of cogenerations in buildings have to satisfy both electrical and thermal demands, which depend on the magnitude of the electrical and thermal load, operating strategy. On the negative side, surplus energy may have to be stored or sold, while deficiency of energy may have to be made up by purchasing electricity and heat from other sources such as utility grid [14]. The excess heat energy produced can be stored in thermal storage devices, such as water tank, while the electricity excess energy can be stored in electrical storage devices like batteries or capacitors. Technologies like fuel cell and engines based cogeneration are promising for small scale cogeneration for residential and commercial building, but currently, internal combustions engines are the only system available at reasonable cost [15]. Therefore, governments especially in Europe, US, Canada and Japan are leading the role in establishing and promoting the development of cogeneration applications, not only in industrial plant, but also in other sectors including commercial and residential building. In Malaysia, cogeneration system has existed for almost a decade now. Several policies for cogeneration projects have been issued in different projects, specifically 13 for public facilities, and one for the private sectors [16]. Regard of government support in providing the incentives and the proven technical viability of cogenerations systems, Malaysia has stepped forward in achievement when in 2007, there were 24 major cogeneration plants in Peninsular Malaysia with a total capacity of 713.2 MW [17]. Numerous articles in related literature discuss about researches to improvise the cogeneration system, covering the area of policies for cogeneration implementation, architecture design, efficiency, control system, optimization, techno-economic analysis and system performances. Cristiano in [18] discussed the policy of opportunistic maintenance, to consider more than one decision criterion by using a multi-attribute value function, for a study developed for a cogeneration system that uses sugarcane bagasse at a power plant in northeastern Brazil. Authors in [19] presented a control system for two cogeneration units and two additional heating plants, where 3000 customers from industry, office building and residential settlements are supplied by the system. A proportional integral (PI) controller tuning method for cooling of the hydrogen production in Proton Exchange Membrane Fuel Cell (PEMFC) based micro-cogeneration was presented in [20]. In this method, the output response attained from the proposed controller is critically damped response with damping ratio, f = 1 and the control signal is slowly varied for safe control signal. Flow rate control of the hydrogen production unit within the micro-cogeneration is implemented by simulating the temperature control system in MATLAB environment. Authors in [21] presented the effect of key parameters on the output power and efficiency in first and second law of thermodynamics point of view. This includes the variation inefficiency and energy destruction evaluation, by evaluating the variations of temperature of high pressure steam, temperature of reheat and condenser pressure in the developed cogeneration system. Authors in [22] discussed the issues on environmental impact of small scale cogeneration facilities, including standalone facilities like thermal storage tank and back-up boiler. The measure data were then used to create dimension of cogeneration facilities to fulfill certain heat demand and study the impact of thermal storage tanks on the operational behavior of 40 different residential heat-demand profiles. S.Shams in [23] introduced a new and simple method to increase the efficiency of on-site distribution generators through cogeneration techniques, whose results were then compared to those of single heat and power techniques. They concluded that the utilization of cogeneration based reciprocate engine can increase the efficiency per consumed fuel while decreasing the gas emissions.

Since renewable energy resources have become famous recently, some researchers tried to integrate renewable energy resources into cogeneration system. Thilak in [24] reviewed the application of various resources of renewable energy, including biomass and solar in the cogeneration system. His review covered the area of design, analysis, modelling and simulation, energy policies, as well as economic and environmental issues. Other than that, [25] presented a development of cogeneration system with renewable energy generation consist of wind energy, PV, heat recovery boiler and battery. The analysis dealt with the problem of operation of cogeneration system, besides discussion on the effect of battery and peak-valley electricity price on system operation costs. A technical, economic and market review of rankine cycle of cogeneration system is described in [26] and the design of micro-CHP for residential utilization is explained in [27]. Reference [28] presents a model of micro CHP system, whose transient analysis had been validated with laboratory results. A wood pellet stirling engine micro-CHP unit is presented [29] to characterize its annual performance when integrated to a building.

Various articles in the literature have described the implementation of cogeneration in power generation. However, these articles only cater the application of the cogeneration system without explaining the concept and principle operation of each cogeneration technology, especially on how prime movers should operate. It is important to identify and understand the performance of cogeneration technologies to select the best for a desired system. While most articles, such as articles [30–36] thoroughly explain cogeneration implementation in power plant, the applications of cogeneration in commercial building such as hospital, airport, shopping complex, university and hotel are still limited, especially in Asian countries like Malaysia. Hence, this study aims to introduce a novel cogeneration system that can be integrated into microgrids, especially in buildings. The operation principle and classification of cogeneration system based on prime movers is described with reference to several related research works. Discussion includes explanation on hierarchical control system designed for cogeneration control system. Furthermore, the application of cogeneration system in several commercial building is comprehensively reviewed. This paper also presents comparison between each prime mover, factors that influence selection of prime movers, challenges and future research directions of the cogeneration system.

This paper starts with Section 1, which presents the background study of cogeneration. Section 2 reviews the application of smart grid, microgrid and cogeneration system, including the standards employed for cogeneration installation and application. Section 3 describes the principle operation of cogeneration, followed by Section 4 which presents the type of cogeneration system and prime movers technology with their application. Section 5 caters discussion on cogeneration control system, including local control, centralized control and decentralized control. Afterwards, Section 6 explains parameters to evaluate cogeneration performance. Section 7 presents the application of cogeneration in various buildings, while Section 8 discusses some cogeneration issues. Challenges and future prospect of cogeneration

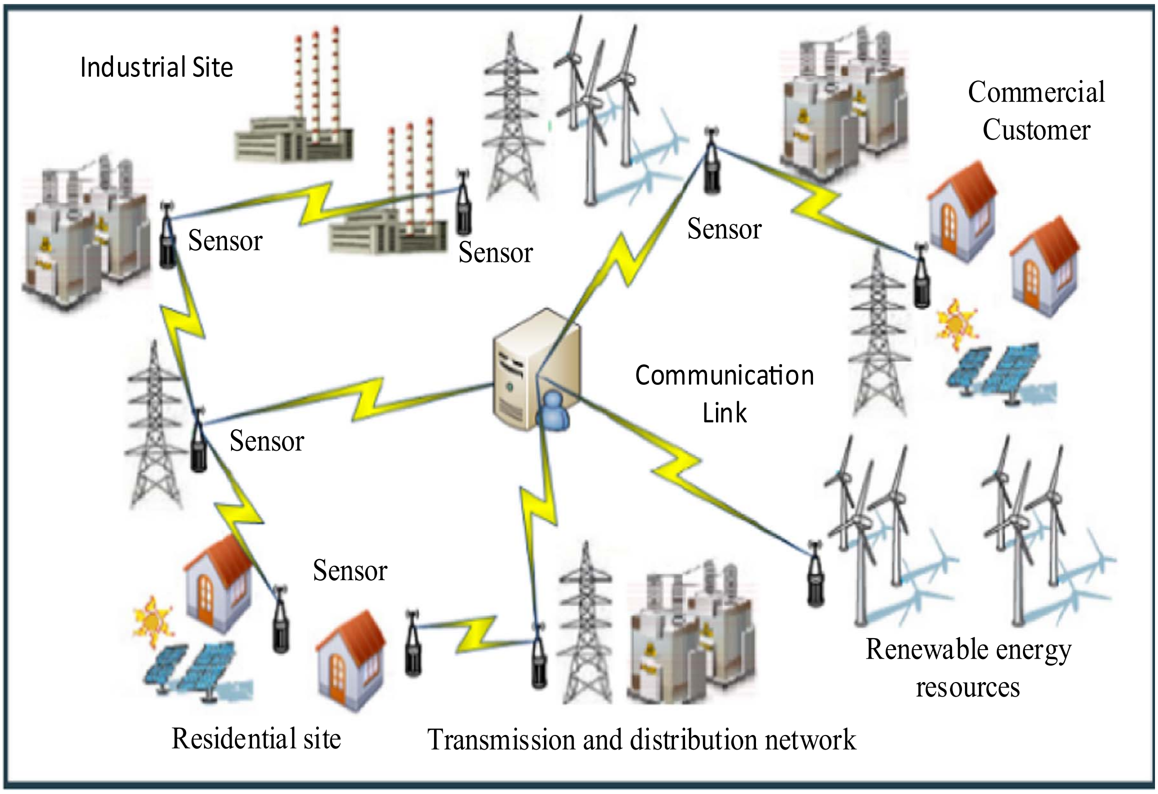

Fig. 1. An overview of smart grid concept.

system is presented in Section 9, then the conclusion of this manuscript is given in Section 10.

2. System description

2.1. Smart grid

Conventional electricity network consists of three main parts which explain power electricity movement from source to consumers, which are generation, transmission and distribution. The existing grid has features of electrochemical structure, one way communication, centralized generation, less sensors, manual recovery, manual checks/test, and some degrees of control by customer [37]. Smart power grid is a more intelligent electrical network, with higher efficiency, flexibility, reliability and security of the electrical system, as the grid is observable, controllable, automated and fully automated, as shown in Fig. 1. Compared to existing electrical grids, Smart Grid (SG) have the features of digital structure, two-way communication, distributed generation, numerous sensors, self-monitoring, self-healing capabilities, remote checks and test, and pervasive control, thus with more customers [38]. Fig. 2 shows the comparison between existing grid and SG system, in which the existing conventional grid has lack of communication capabilities, compared to SG infrastructure which is full of advance sensing, communication and computing abilities [9]. In this case, the issues of reliable and real time information are the key factors for reliable delivery of power from the generating unit to the end users. It is necessary to avoid the effect of equipment failures, capacity constraints and natural accident that cause power disturbances, which is solvable by online power system condition monitoring, diagnosis and protection [39]. SG is expected to have the characteristics of being well-organized and plug-and-play integration of microgrid, to be able to be connected with dedicated highway for exchange of command and data power transfer. Intelligent monitoring and modern communication technologies have become essential to realize the SG features. This means that the infrastructure of information technologies in SG plays a main role. Nevertheless, SG that can be attached with multiple component, including distributed renewable energy resources, distributed energy storage and various levels of load, need to follow standard regulation to ensure smooth implementation [40]. Reference [41] lists the technology and concept of SG including distributed energy resources with generation and storage, advanced and distributed communications whereby all the grid components are able to communicate, and have intelligent metering [42], according to policies and regulatory actions which are necessary to achieve integration of all the parts in SG. More emphases on SG technology can be found in articles [43–45] and [5], which discuss the characteristic, advantages, opportunities, issues and challenges in SG.

Technologies like automated and power electronics are combined in order to achieve the SG performance. Power electronics play the crucial role in smart grid to interface renewable energy resources (RERs) to the grid [46,47]. Besides, it provides necessary control features for controllable power system. Power converters permit the electrical energy consumers to create micro grid that can function independently or in parallel with the main grid. Apart from power electronics roles in energy conversion, energy management system is also critical part to ensure power reliability, efficiency and stability in microgrid system. Energy Management System (EMS), an important module in the scheduling system, is also an important part for micro-grid technology, for data management, monitoring, control and optimization for microgrid dispatch control center. In summary, SG tries to achieve five main objectives, as following:

a. Advance technology to permit the profitable building energy management system to use intelligent control strategies combined with storage system and load generation.
b. Customers to participate in power market, where they can buy and sell electricity based on dynamic rates
c. Demand side elasticity to reduce transmission, energy storage and central generation infrastructure costs
d. Two-way communication between supply and demand allow market

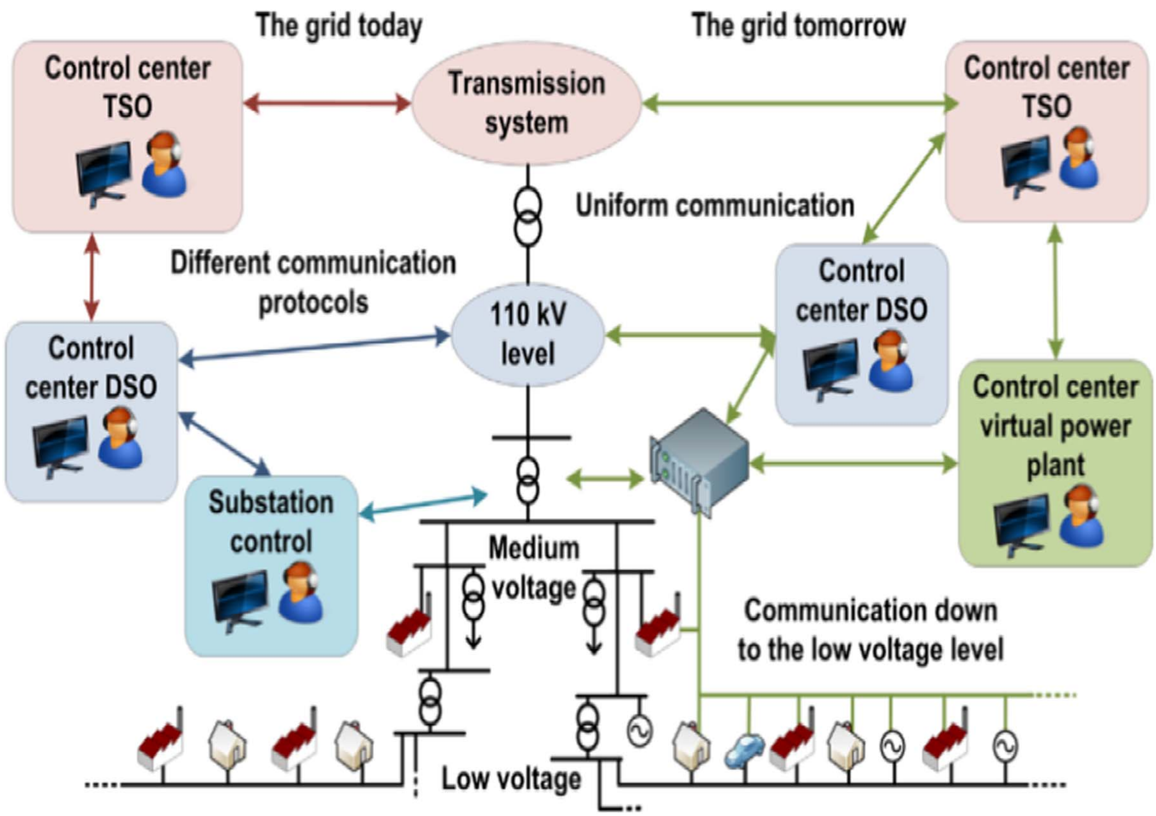

Fig. 2. Comparison of traditional grid information technology with smart grid information technology [40].

signals to propagate to the consumers with load forecast and generation bids going back to the grid controllers and market operators.

e. SG offer electricity product with good quality, carbon content and efficiency

2.2. Microgrid

Microgrid is a low voltage distribution network, formed by distributed energy resources (DERs), energy storage (ESS) and load; all of which participate in active network management of SG [48]. Micro-grid adapts the technology implemented in SG to provide energy services for small communities such as typical housing estate, isolated rural community, mixed suburban environment, academic or public community like university or school, commercial area, industrial site, trading estate and municipal residential [49]. Fig. 3 shows the basic configuration of microgrid, whose architecture basically consists of Distributed Generators (DG), Energy Storage Systems (ESS) and loads. DG resources can be solar PV or wind turbine, while the storage system can be in the form of battery or super-capacitor. The generators may either be one of two types; distributed generation units inside the microgrid control area, which is managed independently from the microgrid manager, and distributed generation units inside the microgrid control area, which is owned by the microgrid manager. These units have micro-sources from renewable energy sources like wind turbine or solar PV. As to ensure system reliability, forecasting must be considered by incorporation of wind or sun characteristic into generation planning. In microgrid, due to large time constants (from 10 to 200 s) of the responses from the resources such as fuel cells and microturbines, a storage device must be able to provide the amount of power needed to balance the system following disturbances or significant load changes [50]. The micro-grid storage system can be in several forms like batteries or super-capacitors on DC bus for each micro-sources, direct connection of ac storage devices (batteries, flywheels, etc.), or use of traditional generation with inertia with the micro-sources. Anitha in [51] reviewed battery technology and concluded that a lead–acid battery is the most suitable for micro-grid applications, because it is capable of providing large currents for a very short interval of time. Basically, there are two types of microgrid, which are AC micro-grid and DC micro-grid; both can operate either in standalone or grid connected mode [52]. During grid-connected mode, they can be controlled as a power node to improve the power flow of power grid, while during islanding mode, it offers high reliability power supply to the critical load. Microgrid operation has four operating stages: 1) transient stage of going to grid-connected mode, 2) steady stage of grid-connected mode, 3) transient stage of going to island mode, and 4) steady stage of island mode. Manager of micro-grid has to ensure every stage's reliability to meet the demand from the load [53,54]. Development of micro grid will become highly important due to its intelligence, flexibility, environmental protection and the diversification of energy utilization in the future.

In microgrid, loads can be categorized into four types, which are critical load, controllable loads, sensitive to price load, and thermal load. Critical load is the demands that must be met at all times, such as servers and loads related to essential processes. In controllable load, the magnitude of certain demands might be flexible. Controllable demand has a preferred level, but the demand level can be lowered if a certain cost is associated with the load shedding. The magnitude of price sensitive load depends on energy price. If energy price is higher than the margin price, load demand will decrease to a predefined value or to zero. Thermal load that requires thermal energy is provided by boiler and recovers heat from microturbine. Another part in the control system is the control system unit for the safe operation of microgrid in various operation modes. The control system unit can be based on central controller or distributed controller. Here, the selection of controller depends mainly on the microgrid operation mode.

Microgrid system not only offers reliable electricity supply but also efficient utilization of the renewable energy. It also reduces carbon

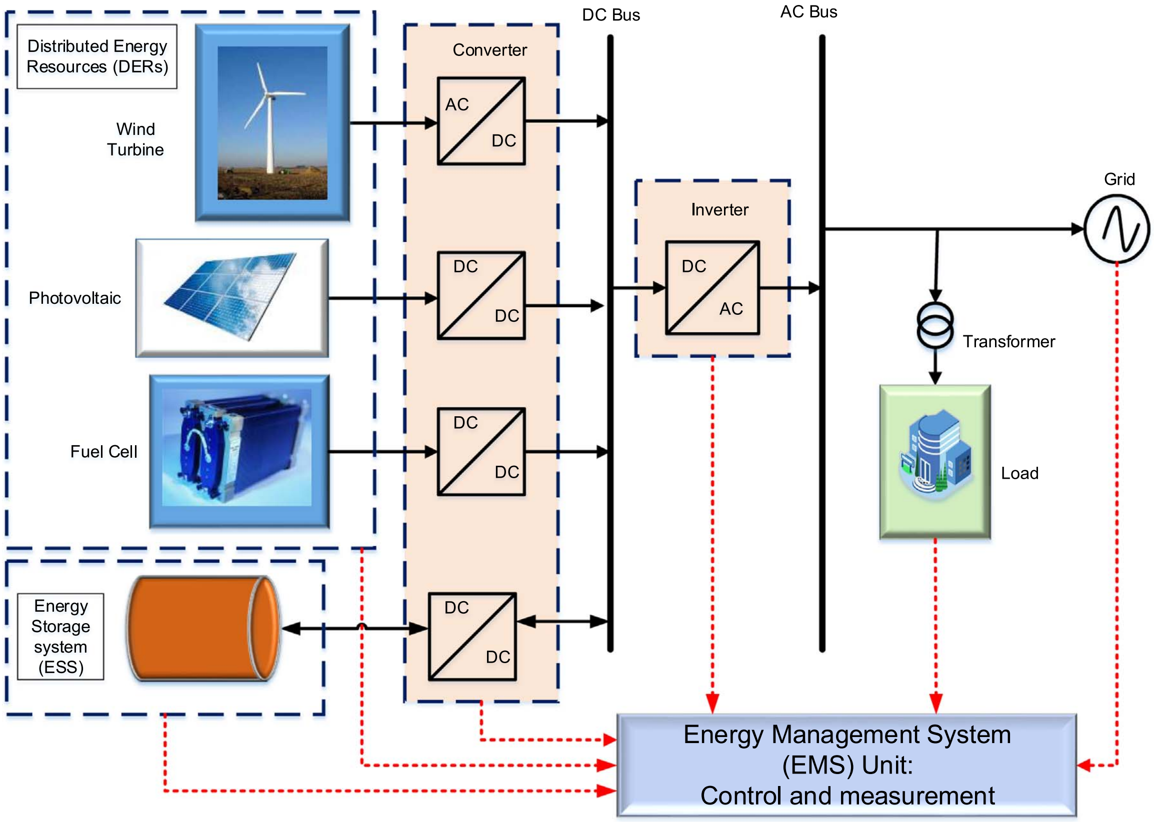

Fig. 3. Basic configuration of micro-grid.

emissions as well as utility bills [55]. Furthermore, microgrid technology provides flexible and high efficiency platform for distributed generation, as well as generation and utilization of renewable energy; in which can improve the utility system performance through cogeneration system or combined heat and power (CHP) system [56]. Prasenjit Basak in [57] and Qiang Fu in [58] explained comprehensively the architecture, controls, protection and demonstrations of micro-grid, while Lidula in [59] presented some existing micro-grid networks in America, Europe and Asia. Taha in [60] conducted an overview on recent research works based on micro-grid area. Indeed, micro grid is interesting due to their tremendous applications, besides its advantages in three different classes: technical, economic and environmentally friendly. From technical point of view, the benefits are such as supporting the power remote communities, higher energy efficiency, less vulnerability of large networks and power blackouts reductions [61]. Microgrid can be designed accordingly to customer's demand such as to enhance local reliability, reduce feeder losses, support local voltages, increase efficiency through the use of waste heat and provide uninterruptible power supply [62]. Basu in [63] reviewed comprehensively the economic benefits of micro grid, like improvement of bus voltages, line loss reduction, reduction in emission, waste heat utilization, interruption cost or the customer, minimization of fuel cost, ancillary services etc.

2.2.1. *Standards in micro-grid*

Since microgrid is a complicated system with various elements attached, several numbers of standards have been developed. One of the most important is the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems 1547. This family standard is developed by the IEEE Standards Coordinating Committee 21, which establishes the criteria and requirements for the interconnection of distributed resources with electric power systems. Although no specific standard has been developed to deal with micro-grids, some of the existing standards for DERs can be adapted to them. Estefanıa in [64] explained the standards used in microgrid to comply with the features in micro-grid. Omid in [65] proposed the applications of IEC/ISO 62264 standards to microgrid and Virtual Power Plant. This standard emphasizes the control method that can be applied in microgrid. According to the standard, control method for microgrid can be explained in five levels, namely generation process level, sensing and adjusting generation level, monitoring and supervising level, maintaining and optimizing level, and market structure and business model level. The levels of control method in this standard are simplified as shown in Fig. 4. Communication standards applied in SG technology including IEC 61970, IEC 61850, IEEE P2030 and ANSI C12.18 have been discussed in article [39]. Authors in [40] presented the main standards specifically needed for SG protection automation. Table 1 lists some of the series of IEC and IEEE standards related to micro-grid work.

2.3. *Cogeneration system*

Recently, cogeneration system or combined heat and power (CHP) system are broadly used in microgrid as to fulfill both electricity demand and thermal loads. Cogeneration system has the ability to generate both electricity and thermal power. During the electrical generation process, a lot of energy is wasted as thermal energy. To take the advantages of the wastes thermal energy, cogeneration system use it to produce the heat with utilize of distributed energy resources such as fuel cells and micro turbine [71]. Meanwhile, the electricity power produced by cogeneration can be used onsite or distributed through the utility grid or both. Cogeneration system has efficiency up to 85% compared to conventional separate energy generation process. Thermal energy is usually used onsite for industrial process heat or steam, space conditioning and hot water. Yet, if the cogeneration system produces more useful thermal energy than needed onsite, it distribution to nearby facilities can substantially improve the cogeneration's economics and energy efficiency. According to [24], cogenerations system is an

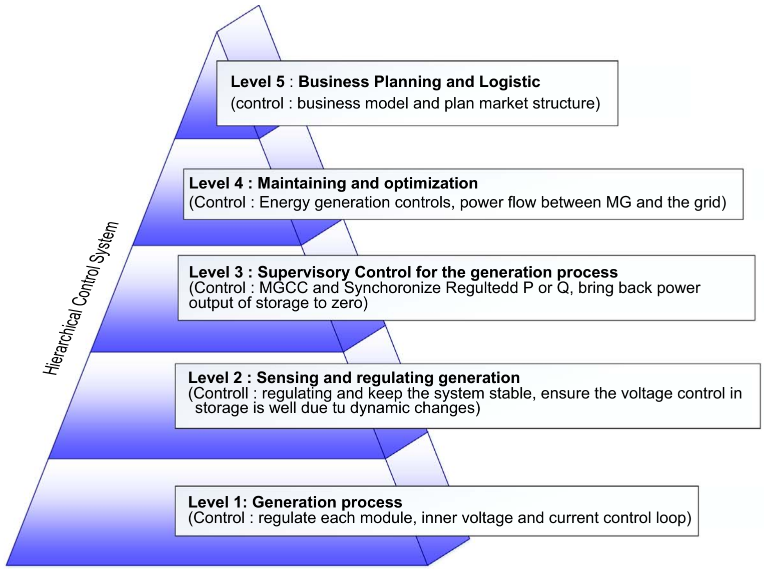

Fig. 4. Control system level suggested in IEC/ ISO 62264 standards.

old and proven practice. However, due to current energy crisis, there has been a resurgence of interest in cogeneration technology for industrial sites, commercial buildings and rural applications. Cogeneration system should provide enough thermal energy to meet many types of industrial demand, such as space heating and cooling for variety of different commercial applications, at the same time supplying significant amounts of electricity to the utility grid. Since cogeneration is able to produce two forms of energy in one process, they can provide substantial energy saving relative to the conventional separate electric and thermal energy technologies. Therefore, cogeneration system is most likely to be competitive with conventional separate electric and thermal energy technologies as it is relatively inexpensively with many benefits. The advantages of cogeneration systems include [72]:

- Less air pollution such as SO_2,NO_x and Hg
- Provide on-site electricity generation that is resilient in the face of grid outages
- Provide power for critical cervices in emergencies
- Avoid economic losses by deferring the investment in new electricity transmission and distribution infrastructure
- Relieve congestion constraints on existing infrastructure
- Require less energy cost, reduce the risk of electric disruptions and enhance energy reliability.

Cogeneration system is also able to predict uncertain electricity

Table 1
List of standards for microgrid [39,64].

Standard	Description	Scopes
IEEE 1547 [45]	Criteria and requirements for interconnection of DERs with the main grid	·1547.1 Conformance test ·1547.2. Application guide ·1547.3. Monitoring and control ·1547.4. Design, operation and integration of DERs ·1547.5. Interconnection guidelines for electric power sources greater than 10 MVA c 1547.6. Interconnection with distribution secondary networks c 1547.7. Distribution impact studies for interconnection of DERs ·1547.8. Recommended practice for establishing methods and procedures
EN 50160 [46]	Voltage characteristics of electricity supplied by public distribution networks	·Definitions and indicative values for a number of power quality phenomena in LV and MV networks ·Limits for power frequency, voltage variations, harmonics voltage, voltage unbalance, flicker and mains signaling
IEC 61000 [47]	General conditions or rules necessary for achieving electromagnetic compatibility	·Safety function and integrity requirements ·Compatibility levels ·Emission and immunity limits ·Measurement and testing techniques ·Installation guidelines, mitigation methods and devices
IEEE C37.95 [48]	Protective relaying of utility-consumer interconnections	·Establishment of consumer service requirements and supply methods ·Protection system design considerations
IEC 61850 [66]	Communication	– Data exchange – Power network parameters
IEC 61970-301 [67]	Energy management system	– To ensure reliable operation of the interconnected power networks
IEC 62325 [68]	Energy market	– A framework for energy market communication – Business operational view with technical e-business architecture
IEC 61968 [69]	System interface	– System interface for distribution management
IEEE 37.118 [49,70]	IEEE Standard for Synchrophasor for Power Systems	·Definition of a synchronized phasor ·Time synchronization, application of time tags ·Method to verify measurement compliance with the standard ·Message formats for communication with a PMU

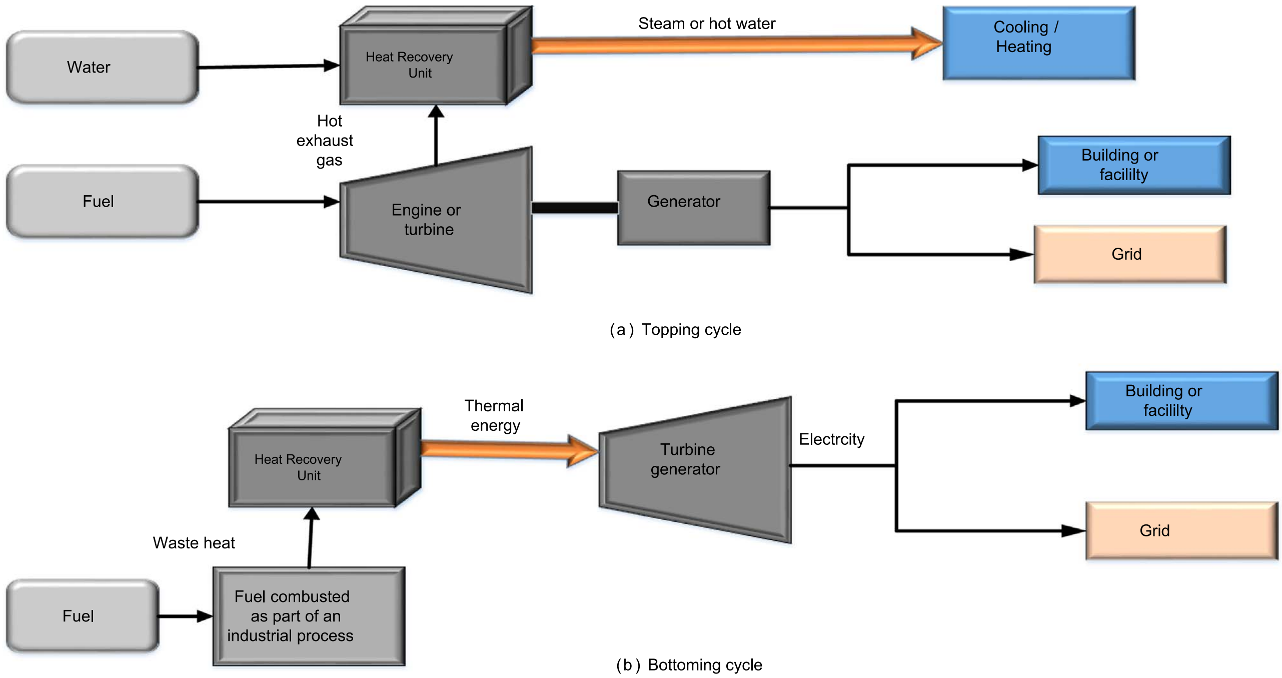

Fig. 5. Topping and bottoming cycles in cogeneration system.

price. Because of this, buildings like hospitals, schools, university campuses, hotels, nursing homes, office buildings, single or multi-family houses and apartment complexes takes the benefits of cogeneration system to meet their power demand [73]. As an example, hospitals that use both electricity and thermal energy, taking advantage of favorable utility rate and hedging against rising electricity prices. Instead of purchasing electricity from the local utility and burn conventional fuel in an on-site furnace or boiler to produce thermal energy, hospitals can use cogeneration system to provide both energy services by one energy efficient method. The applications of cogeneration in buildings must satisfy both electric and thermal demands. Wen-Tien Tsai in [74] performed an analysis of cogeneration system installed in Taiwan. In the study, electricity supply, consumption and sources during past two decades, 1984–2004 were analyzed. Meanwhile, researchers in reference [75] developed a model of optimal energy planning for a commercial building by integrating solar and cogeneration system.

Compared to conventional generation system, cogeneration can reach up to 80% of efficiency. Efficiency of the cogeneration system determines the performance of cogenerations implementation [30]. In this regards, the efficiency of the cogenerations system depends on the type of the prime mover, its size and the temperature at which the recovery heat can be utilized. The efficiency is generally expressed in both electrical efficiency and overall efficiency, as in Eqs. (1′) and (2′) [30].

$$\text{Electrical efficiency} = \frac{\text{electrical output}(\text{kW})}{\text{fuel input}(\text{kW})} \tag{1′}$$

$$\text{Overall efficiency} = \frac{\text{usefull thermal} + \text{electrical output}(\text{kW})}{\text{fuel input}(\text{kW})} \tag{2′}$$

Integration of cogeneration system into smart electric power system requires a sophisticated and automated control system for energy management supervision. This is to ensure the operations of the cogeneration system in accordance to the power and heat demand of the consumers. The operation schedule of the cogeneration system will be calculated by an optimization tool, based on a forecast of the power and heat demand. Optimization tools are based on mathematical models that describe the relations between the main influence factors and the power and heat demand. Cogeneration system requires large number of relevant information, since efficient data management is necessary to control the cogeneration system. A control strategy for cogeneration system is described in upcoming sections.

3. Principle operation of cogeneration system

There are three main operations in cogeneration system, which are topping cycle, bottoming cycle and combined cycle. Mostly, cogeneration is operated in topping cycle, where fuel is first used to generate the electricity or mechanical energy at the facility, and a portion of the waste heat from power generation will be used to provide useful thermal energy. In typical topping cycle of cogeneration system, fuel is used by prime mover to generate electric or mechanical power. The produced electricity may be used for the building and facilities, or it will be transferred to the power grid. Next, the prime mover's hot exhaust is used to provide process heat, hot water or space heating for the site. Topping cycle plant focuses on generating electricity and selling excess electricity to an electricity utility, and this plant is usually sized to meet the heat demands of a site, with consideration of electricity generations being a secondary. The topping cycle plant always requires additional fuel which is included in the operational cost along with power production. Meanwhile, bottoming cycle type of cogeneration systems first produces useful heat for a manufacturing process by fuel combustion or any heat-generating chemical reaction, and recovers some portion of the exhaust heat to generate electricity. Bottoming cycle is also referred as Waste Heat to Power (WHP) and it is mostly applied in process industries, like glass and steel where very high temperature is needed. A percentage of the rejected heat is then recovered and used for power production in building, facilities or grid [10]. Fig. 5(a) and (b) show the topping and bottoming cogeneration principle operations, respectively. In the latest technology, the topping and bottoming cycle is joined together to form combined cycle with better efficiency, as shown in Fig. 6.

4. Technology in cogeneration system

Basically, a cogeneration system consists of generators, heat recovery and electrical interconnection component. Cogeneration technology is categorized according to their prime movers or the heat

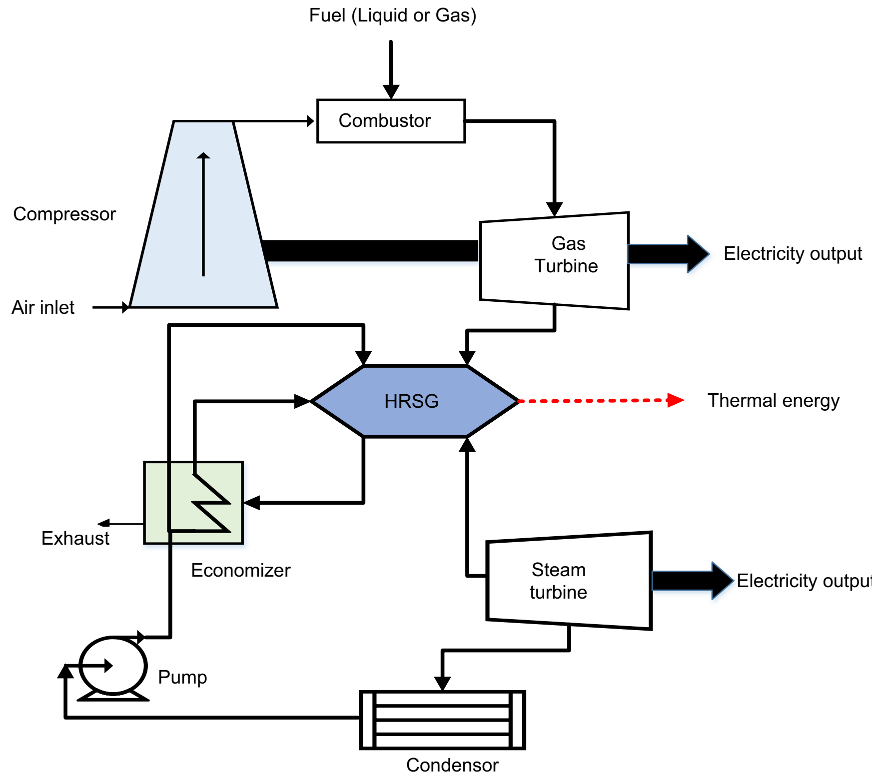

Fig. 6. Block diagram of combined cycle cogeneration.

engines. The role of these prime movers is to burn a variety of fuels, including natural gas, coal, oil and alternative fuel in order to produce shaft power or mechanical energy. Besides being used to drive a generator to produce electricity, the mechanical energy from the prime mover can also be used to drive rotating equipment like compressors, pumps and fans. Combustion process by prime movers consumes fuel such as coal, natural gas and biomass to power the generator to produce electricity or drive rotating equipment. Besides, prime mover will produce thermal energy that can be captured and used for other onsite processes to generate steam or hot water, heat air for drying, or cool water for cooling purpose. Prime movers in cogeneration system as stated in the literature can be classified into two classes, which are combustion-based technology and electrochemical based technology. In the current market, there are five primary commercially available prime movers for cogeneration system: gas turbines, steam turbines, reciprocating engines, micro turbines and fuel cell. Each of this technology is explained in the following subsection.

4.1. Gas turbines

Gas turbine cogeneration system is highly reliable as it has capacity between 500 kW and 250 MW, and can be used for high-grade heat applications. Gas turbine for cogeneration system consists of generator, combustion chamber, recupator, compressor and turbine connected by a shaft [76]. The operation of gas turbines is similar to that of jet engines, where natural gas is combusted and used to turn the turbine blades; and it will spin an electrical generator. Then, the integrated heat recovery system will capture the heat from the gas turbine exhaust stream. The exhaust heat produced can be used for heating or cooling purpose. The heat from the system is also recovered from the hot exhaust gas using a heat recovery system. Fig. 7 shows a basic cycle of gas turbine cogeneration system recovering heat from the gas turbine's hot exhaust gases to produce useful thermal and electrical energy for the site consumption.

There are numerous studies in literature which focused on the gas turbine application. Wang Shen in [77] analyzed the characteristic of energy consumption of the demand side system of cogeneration system with micro gas turbine. The fuel saving rate for different running condition was evaluated in this study, inclusive of a comparative study for the systems with and without auxiliary fuel supply for the absorption. Results of this study showed that under special condition where the efficiency for power generation plus grid is less than 34.5%, the output will save the energy. Researchers in [78] optimized the sizing for a gas fired grid connected cogeneration system planning in Malaysia, whereby the optimization approach was presented. This is a parallel study, as currently, the Malaysian government is encouraging the development of cogeneration by utilizing renewable energy resources, along with introduction of some policies [79]. Meanwhile, researchers in [80] conducted a study to improve the operational parameters for natural gas in cogeneration plant in public building in Thailand. Two case studies were conducted in order to study the alternatives parameters. The first one was conducted on a 52.5 MW cogeneration plant at the Suvarnabhumi Airport and the second was on a 9.9 MW cogeneration plant of the government office building complex. The Suvarnabhumi Airport uses District Cooling System and Power Plant (DCAP), which is a natural gas based cogeneration plant designed for supplying electricity, and providing steam and chilled water for cooling purposes at the airport area, with a total capacity of 52,5 MW electrical power and 25,240 RT (88,765 kW) of cooling energy. Another case study was done on a cogeneration plant designed to supply electricity and cooling at the new government office building complex, which houses offices, restaurants and shops that open from 8.00 A.M. to 5.00 P.M. from Monday to Friday. The plant utilizes natural gas based cogeneration with 9.9 MW electricity and 6000 RT (21,000 kW) cooling capacity. The parameters of efficiency had been measured and compared in this study, which showed that the improvement of the system's efficiency is important, not only for operating performance, but also for savings of primary energy and emissions. Therefore, the selection of new prime mover resulted in overall efficiency improvement from 48% to 61%; 24% increase in

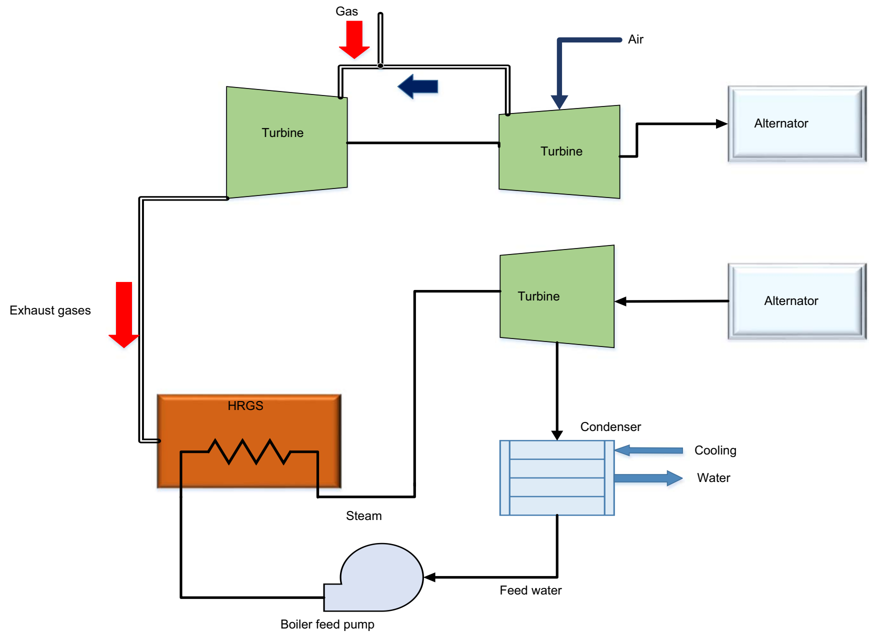

Fig. 7. Block diagram of a typical gas turbine cogeneration structure.

primary energy saving and 27% improvement of CO2 emission reduction. In another study reported in [81], a hybrid cogeneration plant consisting of three 46 MW gas turbines units and one 36.6 MW steam turbine a gas turbines was developed. The cogeneration plant was designed to improve the power service quality in the Hsin-Chu Science-based Industrial Park. Article [82] presents a development of combination gas turbine-steam turbine combined cogeneration system. This study intended to analyze the energy consumption by new constructed tool in Korea in order to forecast the liquid petroleum gas (LPG) demand in 14 years. Meanwhile, [83] presents a cogeneration system consisting of a gas turbine with two-cycle process, installed at the University Campus in Trsat and the new Clinical Hospital Center in Rijeka, to generate steam for heating and produce electrical energy. According to the design, the university campus will be supplied with a natural gas from the main gas line, which is high-pressured gas. Gas pressure will be reduced from high pressure ($4e^6$ bar) to moderate pressure (up to 1 bar) at the gas measuring and regulation station, which will be located in the university campus area. Articles [84,85] presents investigation on gas turbine application, by demonstrating the operation of micro gas turbine cogeneration system with latent heat storage at the Energy Technology Research Institute of the National Institute Advances Industrial Science and Technology. A 30 kW Capstone micro gas turbine with hot water package and a vacuum-type hot water were used in the experiment. The exterior of the latent heat storage tank was made of SUS304 stainless steel, with height of 1.8 m and 348 mm in diameter with 96 capsules. Detailed explanation is discussed comprehensively in the provided reference. Anita in [86] presented an efficient nonlinear programme (NLP) model for simultaneous cogeneration system of electricity by using an open gas turbine for an exothermic reactor circuit system.

4.2. Steam turbines

Steam turbines cogeneration system may use variety of fuels such as natural gas, solid waste, coal, wood, wood waste and agricultural byproducts to generate electric and thermal power. A general steam turbine diagram is shown in Fig. 8 while Fig. 9(a) and (b) illustrate several types of steam turbines, including back pressure and condensing. In back pressure turbines, exhaust steam is at a pressure higher than the atmosphere, but in condensing turbines, the exhaust steam is at pressure lower than atmosphere. Hence, condensing turbines produce more electricity per unit of fuel compared than back turbines. This is because, more energy contained in the steam is extracted by the turbine [87].

Normally, steam turbines have capacity between 50 kW to 250 MW, and work by combusting fuel in a boiler to heat water to create high-pressure steam, which will turn a turbine to generate electricity. The low-pressure steam output from the steam turbine can be used to provide useful thermal energy either in buildings, factory or utility grid, as illustrated in Fig. 10. Numerous researches have been done to investigate the application of steam turbine for cogeneration system. However, it is beyond this study to discuss all the related articles. Therefore, only several of them are highlighted. As example, Amit in [31] found that the generated power by 35 TPH boiler in 6 MW captive power plant can have the largest destruction energy. Marshman in [88] developed a steam-based cogeneration system to provide heat for pulping process, and to generate electricity for sale to regional providers. Meanwhile, article [89] presents a comparison between the performance of a cogeneration system based steam turbine and conventional diesel steam boiler. The work aimed to solve the dilemma to replace the traditional generation system with new cogeneration system. The initial modelling work of steam turbines cogeneration was followed by calculation of total expected setup and operational cost of steam turbines cogeneration. K.Alanne in [90] characterized a boiler-integrated rotary steam engine (RSE) micro-cogeneration system and specified a two-control volume thermodynamic model to conduct performance analysis in residential applications. The finding showed that the RSE integrated with a 17 kWth pellet-fuelled boiler could obtain an electrical output of 1.925 kWe, at temperature of 150 °C, reaching electrical efficiency of 9%, based on the lower heating value of the fuel, LHV and thermal efficiency of 77% (LHV). The above system can operate up to 1274 h per year in a single family house in Finland, meeting 31% of the house electrical demand. The amount of electricity delivered into the grid is 989 kW h/y. Rodrigo in article [91] showed how thermo-economic models can be adapted to allocate overall CO_2 emission of four different gases and steam turbine cogeneration systems to the final products (net power and heat). In thermo-economic analysis, a single model of Second Law Thermodynamic analysis is combined with economic factors, which one must consider in the design and/ or performance evaluation and optimization of any energy system. Article [92] presents investigation on a modified operation in steam injected operation. In this work, simulation was

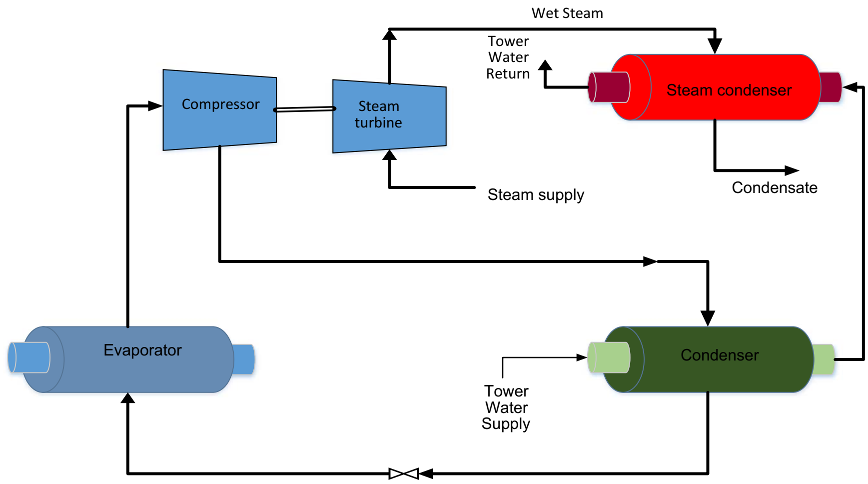

Fig. 8. Block diagram of a general steam turbine cogeneration system.

done on 5 MW class gas turbine cogeneration plant, by injecting steam to analyze the influence of bypassing some of the discharged air from the compressor to the turbine exit on the operability.

4.3. Reciprocating engines

In many cases, reciprocating engine cogeneration systems are well suited to various distributed generation applications, industrial, commercial and institutional facilities. Reciprocating engines or reciprocating internal combustion engines are suitable for small scale cogenerations applications due to their robust and well proven technology. They can start quickly, follow load well, have good part-load efficiencies and have high reliability as well as able to increase overall plant capacity and availability. Besides, reciprocating engines have higher electrical efficiency compared to gas turbines, thus lower fuel-related operating costs. In addition, the initial cost of reciprocating engine generator sets is generally lower than gas turbines generator sets of up to 3–5 MW in size. Reciprocating engines also can be operated by using broad variety of fuels with excellent availability. However, the maintenance cost of reciprocating engines is higher compared to the gas turbines, but the maintenance can often be handled by in-house staff or provided by local service organizations. Usually, reciprocating engines are in use of standby, peak shaving, grid support, and CHP small applications of less than 5 MW such as hot water, low pressure steam or waste heat absorptions. Fig. 11 shows the principle operation of reciprocating engines cogeneration system. There are two sources of heat for recovery purpose. The first is exhaust gas at high temperature and the other one is engine jacket cooling water system at low temperature. Generally, reciprocating engines are classified based on their method of ignition, either compression ignition (diesel) engines or spark ignition (Otto) engines [93]. Normally, diesel engines are used for large scale cogeneration. These engines have four stroke direct injection engines fitted with a turbo-charger and intercooler. Diesel engines run on diesel fuel (sometime heavy oil) but they can also be set up to operate on a dual fuel mode; in which they can burn primarily natural gas with small amount of diesel pilot fuel. Stationary diesel engines can operate at speeds between 500 and 1500 rpm. However, the cooling system for diesel engines are more complicated compared to cooling system in spark ignition engines since the temperature in spark ignition is often lower (usually 85 °C maximum)[94]. In comparison to diesel engines, spark ignition engines have heat recovery system normally up to 160 °C of hot water or 20 bar steam output, which is more suitable for smaller cogeneration applications such as residential and open chamber engines. Normally, spark ignition engines run on natural gas although they can operated by using propane, gasoline or landfill gas [93,94]. There are six main components of reciprocating engines, which are the engine, generator, heat recovery system, exhaust system, controls and acoustic enclosure [93]. A spark ignition engine consists of four main parts, which are the exhaust gas heat exchanger, jacket water heat exchanger, lube oil heat exchanger, valve and generator, as shown in Fig. 11 [93]. The operation in the engines starts with fuel and air being mixed, usually before introduction into the combustion cylinder for spark ignited units. Next, the air is compressed before mixing with the fuel. The fuel or air mixture is then introduced into a combustion cylinder that is closed at one end and contains a moveable piston. After that, the mixture is compressed by the piston, which moves toward the top of the cylinder.

Although numerous research works have employed reciprocating engines as their cogeneration system, it is beyond this article to discuss all. Nevertheless, this section will highlight several references related to

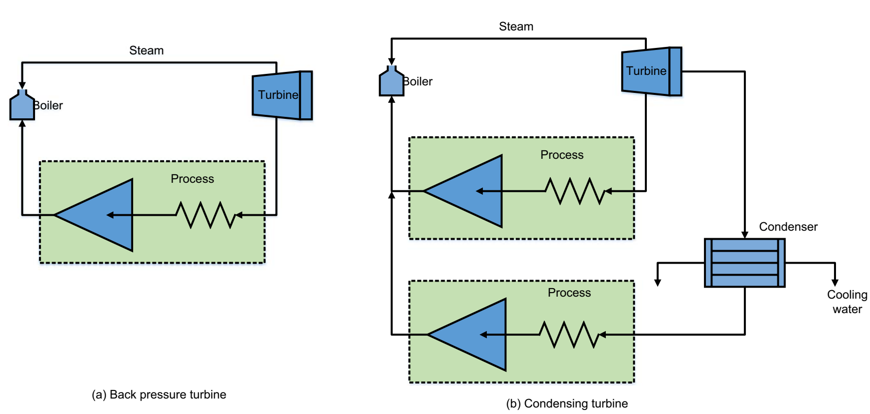

Fig. 9. Schematic diagram of steam turbine cogeneration, (a) back pressure turbine, (b) condensing turbine.

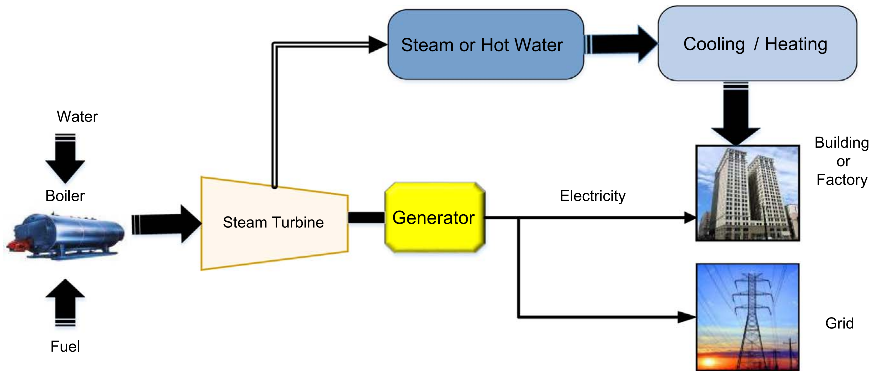

Fig. 10. An example of steam turbine with boiler cogeneration application for buildings, factory and grid.

the study scope. Muccillo in [95] designed a micro cogeneration system based on reciprocating engines. A plant was built, with installation of Lombardini 686 cm^3 twin cylinder reciprocating engine with a volumetric compression ration equal to 10.5 unit. L.Federick in [96] conducted a dynamic simulation for a small Joule cycle reciprocating Ericson engine for micro-cogeneration. In this study, both pressure losses and the variation of the thermos-physical properties of the working fluid were considered as a function of the temperature in the system. The models developed in MATLAB environment took into account the optimal settings of the expansion cylinder valves, and the characteristic parameters of the engine were determined. K.T.Yun in [97] presented a power generation and heat recovery model for reciprocating engines to serve as an alternative to constant engine efficiencies or empirical efficiency curves. Article [98] presents a theory of thermodynamic heat-engine concept which has the potential of attaining a high efficiency and power density relative to competing solutions, while having a simple construction with few moving parts and dynamic seals, allowing low capital and operating costs, and long lifetimes. In this study, a spatially lumped dynamic model of a class of unsteady heat-engine referred to as the 'Evaporative Reciprocating-Piston Engine' (ERPE) had been developed as an electronic circuit representation, which was then compared to fundamental reciprocate engines. Yunjin in [99] investigated the effects of biogas composition on the combustion characteristics for stirling ignite engines. The finding of this study concluded that a significant reduction in NOX emissions could be expected when using biogases containing CO2; however, an increase in fuel consumption would be unavoidable. A lean burn strategy is effective for reducing both fuel consumption and NO_X emissions; however, the use of biogas with stoichiometric air–fuel ratio (which can better handle transient operating conditions) would be more effective in reducing NO_X emissions and can improve the fuel economy at higher loads. Reciprocating engines based cogeneration also can be employed for residential load, as proposed and proven by a study in article [100]. In the study, cogeneration based stirling engines were used to supply the residential area which have 8 kW of hot water and 1 kW electricity. Three test cases were considered by fixing the temperature of the cogeneration water at the unit inlet alternatively: 30, 50 and 70 °C, while the mass flow rate of the water was kept at the nominal value of 0.194 kg/s. The Stirling unit showed electrical efficiency slightly exceeding 9% and a thermal efficiency of 90% (both based on the Higher Heating Value) when the cogeneration water inlet temperature was 30 °C, which decreased to about 84% with water inlet at 70 °C. The Primary Energy Index was remarkably positive for all cases, ranging from 17% to 22%, as the temperature of the water inlet reduced from 70 °C to 30 °C.

4.4. Microturbine

Microturbine are small combustion turbines that burn gaseous or liquid fuels to drive electrical generator. Micro turbines are similar to gas turbines in their design and construction. They have been commercially used for more than a decade because of their small and compact size, besides having lightweight combustion turbines with high efficiency [101]. Other advantages of micro turbine are flexibility in connection method, able to stack in parallel to serve larger loads, can provide reliable and stable power, and produces lower emissions compared to reciprocating engines. The power output from micro turbines is typically within 33,030–330 kW. Normally, thermal energy

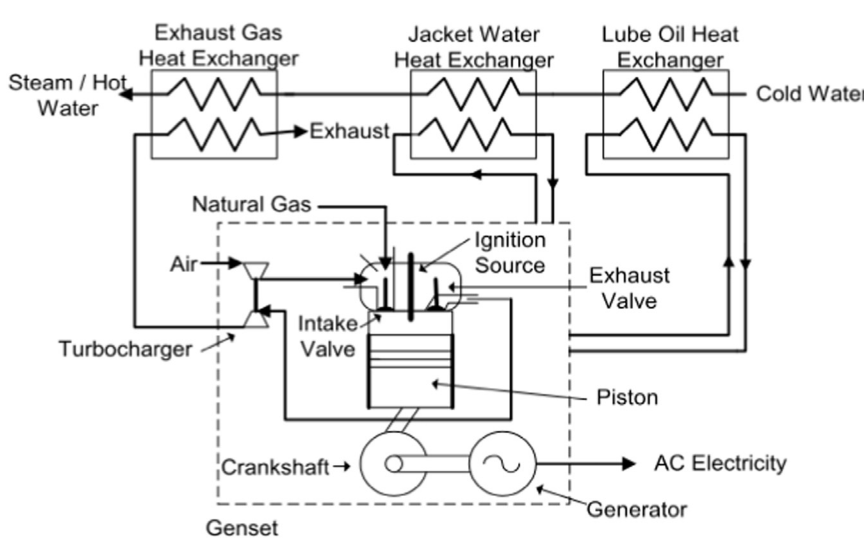

Fig. 11. Schematic diagram of spark ignite engine (reciprocating engines) [93].

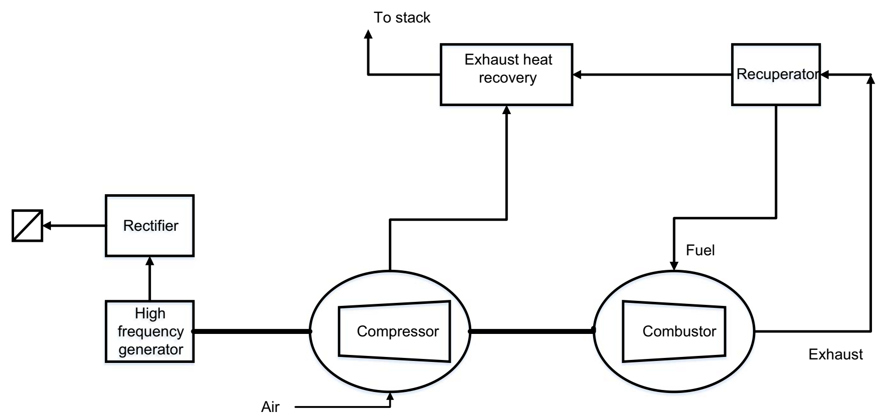

Fig. 12. An overview block diagram of microturbine cogeneration system.

Table 2
Important attributes of microturbine.

Electrical output	Within 33,030–330 kW with modular package up to 1000 kW
Thermal output	Temperature within 533 K to 589 K (260 °C to 316 °C), suitable for supplying thermal needs such as hot water and steam. Besides, a thermal energy storage will be used to store chilled water in order to provide cooling output [105].
Fuel flexibility	Can use various types of fuel: natural gas, sour gas, liquid fuels (gasoline, kerosene, diesel fuel, heating oil)
Reliability and life	40,000 to 80,000 h with overhaul
Emissions	Low NOx combustion when operating in natural gas
Modularity	Units may be connected in parallel to serve larger loads and to provide power reliability
Part-load operation	Units can be operated to follow load with some efficiency penalties
Dimensions	Compact and light weight, 0.7–0.85 m and 18–23 kg/kW

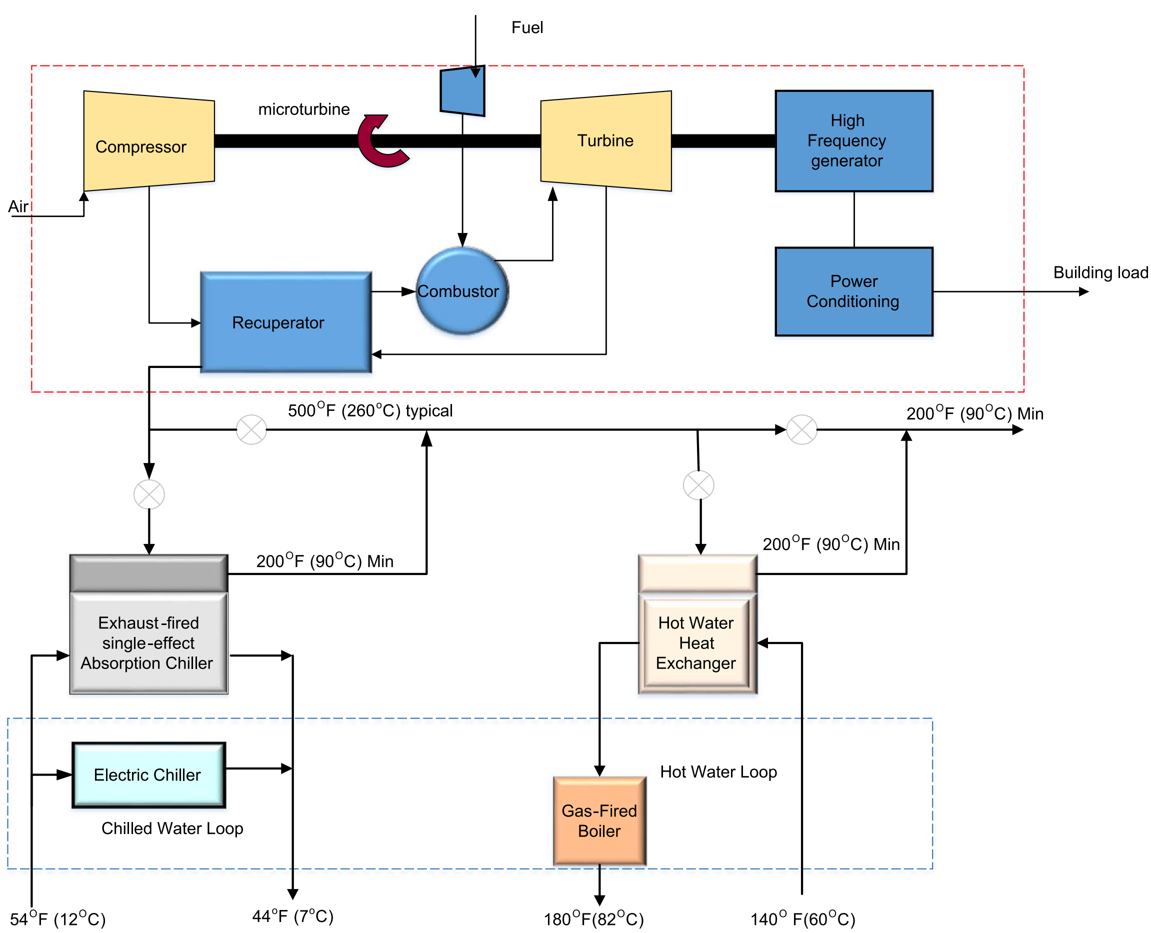

Fig. 13. Schematic of microturbine based cogeneration system.

from heat exchanger will be used for portable water heating, absorption cooling, space heating, process heating and other building uses [102]. Microturbine are lightweight and compact, and has low noise, vibration and low emissions, compared to combustion engine generators (reciprocating engines). Furthermore, microturbine are flexible in fuel type and can burn various fuel including natural gas and liquid fuels. Fig. 12 presents the basic micro turbines components which are the combined compressor or turbine unit, generator, recuperator, combustor, and heat exchanger. A microturbine has eight main attributes that show microturbine characteristic; electrical output, thermal output, fuel flexibility, reliability and life, emissions, modularity, part load operation and dimensions, as shown in Table 2 [103]. Fig. 13 illustrates schematic of typical microturbine that provides power, heating and cooling system. The operation starts with the compressor section raising the air pressure equal to atmosphere pressure, then the air enters a recuperator that preheats the air using turbine exhaust. Next, the heated air enters the combustor, where pressurized fuel is injected and burned. Since commercial buildings are typically supplied with low-pressure natural gas, a compressor generally is needed to pressurize the gas prior to injection. After combustion, the exhaust products enter the turbine, which provides shaft power to the compressor and a generator. The generator typically produces high-frequency power, which is changed to desired frequency (50 Hz or 60 Hz). The turbine exhaust gas, which is typically at temperature of about 1100OF (600 °C), enters the recuperator. Next, the exhaust gas (typically at 500°F(260 °C)) is either released into the atmosphere, or into one or more heat-recovery heat exchangers to produce heating or cooling loads for the cogeneration system [104].

Since microturbine technology have various advantages, numerous researches have been done utilizing micro turbines as prime mover in cogeneration system. This section presents several works on micro turbine application. Ismail conducted a technical and economical modelling of microturbine for hybrid renewable energy resources, as in reference [106]. The study found that microturbine offer more advantages compared to reciprocating engines, which include long lifetime (about 45,000 h), light weight, small size, small number of moving parts, fast response, higher efficiency, lower emissions, lower electricity costs, higher flexibility and opportunities to utilize waste fuels with less noise. Researchers in [107] also studied the applications of micro-turbine as the prime mover of CHP system. In this work, the prime movers is properly sized with the development of technical-economic approach to select the optimum arrangement of microturbine. Three modes of operation were projected: one-way connection (OWC) mode, two way connection (TWC) mode and heat demand following (HDF) mode. Articles [108] and [109] catered modelling and simulation of microturbine based on GAST model developed by General Electric [110]. An experiment to develop micro turbines is presented in article [111]. The result of this experiment confirmed the possibility of micro turbine for developing ICE by utilizing turbocharger with reversible electric machine to improve engine performance. The development concept was based on unification of micro turbine with mass production of turbocharges and generators. Micro turbines also can be used as a backup generator by combination with fuel cell and battery storage, as performed by the researchers in article [112]. The main objective of this work was to control the microgrid consisting of several generator accompanied by a back-up microturbine, fuel cell and battery, whereby the work stress up to the energy management strategy employed Adaptive Modified Particle Swarm Optimization algorithm (AMPSO). The microturbine, fuel cell and battery functioned to solve the level of power mismatch or to store the surplus energy until needed. Article [113] presents technical testing for characterisation of micro Humid Air Turbine (mHAT) based recupator micro turbine. This experiment work was done at Vrije Universiteit Brussel (VUB), by using T100 mGT equipped with a spray saturation tower. The study demonstrated the performance of water injection in micro turbine could increase more than 30%, while the fuel consumption would rise only by 11%, which actually would increase the electrical efficiency of the cogeneration system.

4.5. Fuel cells

The latest technology in cogeneration prime movers is utilizing fuel cells, as fuel cells are capable to serve power and thermal needs with very low emissions and with high electrical efficiency [101]. In [114], J. Halliday reported that fuel cell is becoming famous due to its efficiency in providing heat and power for urban application. The type of fuel cell determines the temperature of the heat liberated during the process and its suitability for cogeneration applications [115]. There are two types of fuel cell classified based on the temperature level. Proton Electrolyte Membrane Fuel Cell (PEMFC) is usually used for low level temperature, since it generates thermal energy suitable for low-pressure steam and hot water in cogeneration system. Solid oxide fuel cell (SOFC) is used for high temperature application, such as combined cycles and other cogeneration process applications, because it can work at a very high temperature, around 800– 1000 °C. Basically, fuel cell uses an electrochemical reaction or battery-like process to convert chemical energy, for example hydrogen into water and electricity, through electrolysis process. Hydrogen can be obtained by processing natural gas, methanol, coal or other hydrocarbon fuels. In fuel cell, the electrochemical reaction between hydrogen and oxygen will release chemical energy, which will then be converted into electrical energy. Reference [116] comprehensively reviews the history, advancement in technology, advantages and challenges, stationary and portable, design level and methodology, system evaluation factors and thermodynamic principles in fuel cell. Fig. 14 shows an internal structure of fuel cell conversion flow, in which an electrolyte combines hydrogen with oxygen from air to produce hot water or steam and electrical current. As shown in the figure, molecular hydrogen is delivered from a gas flow stream to anode as it will react electrochemically. Then, the hydrogen is oxidized to produce hydrogen ions and electrons, as described in Eqs. (1)–(3) [116].

Ions that migrate through the acidic electrolyte and the electrons are forced to flow through an external circuit, to reach the cathode, as in Eq. (1). Next, the electrons and hydrogen ions will react with oxygen supplied from external gas flow at the cathode, to form water, as in Eq. (2). Lastly, the chemical reactions in the fuel cell produce water, heat and electricity, as described in Eq. (3).

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + W_{elec} + Q_{elec} \tag{3}$$

Fuel cells are categorized according to the material used for the electrolyte. There are five types currently under development:

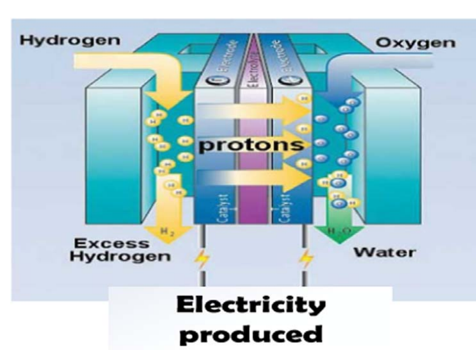

Fig. 14. The illustration of the electrochemical process flow in the internal structure of a fuel cell.

Table 3
Domain specific studies employing fuel cell for cogeneration system.

Domain	Finding	References
Control system	New methods and techniques have been proposed to control fuel cell and supercapacitor, by using simple and effective algorithm to produce references. Simulation results of the hybrid system (solar, fuel cell and battery) shows good respond. Control strategy eliminates the need for dump load by limiting the power drawn from the sources.	[117,118,137]
Energy management system	The supervisory control introduced in the energy management system is essential to ensure optimum reliability and cost of the hybrid system (fuel cell and renewable energy sources).	[138–143]
System sizing	Optimization sizing methods to optimize the size of hybrid components, using fuel cell as the hydrogen storage, in order to achieve optimum system reliability as well as not to oversize the system components.	[120,129]
Characteristic and performance of fuel cell	Dynamic model of fuel cell has been used to examine and analyze the characteristics of Ballard Nexa 1.2 kW PEMFC to obtain accurate dynamic performance in simulation. The accurate dynamic model is significant to evaluate the feasibility of fuel cell application in buildings.	[119,121]
Techno-economic	Various studies have been conducted using different simulation tools to assess the economic feasibility for buildings employing cogeneration based system.	[124,125,144–149]

Phosphoric Acid fuel cells (PAFC), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), alkaline fuel cells (AFCs), and proton exchange membrane (also called as polymer electrolyte membrane) fuel cells (PEMFCs). Among them, PEMFC is operated under low temperature, while the others operate at higher temperature. Article [116] provide a comprehensive review of fuel cell technology including history, competing technologies, design thermodynamic and electrochemical principles of fuel cell. Fuel cell has quiet operation and could be sited almost everywhere. As there are many advantages of fuel cell, there plentiful research work on fuel cell based cogeneration system is performed. Recently, fuel cells are being used in hybrid technology, which combines the fuel cell with other types of renewable energy. References [114,117–129] circle around studies on control system, sizing and system behavior of fuel cell. Table 3 presents some domain studies on of fuel cell in energy management system and techno-economic feasibility, which also prove that fuel cell is the most preferred energy supplier for cogeneration application. Zehra Ural in [130,131] designed and developed PEMFC, while El-Sharkh in [132] analyzed the economic output of fuel cell using the evolutionary programming based methodology. Sheila in [133] modelled micro-generation based on fuel cell, by integrating the stack with necessary sub-systems for it to operate as a residential heat and power generator. References [126] and [128] catered about dynamic modelling, simulation and optimization, by simulating combination of fuel cell with other renewable energy resources to observe the behavior of fuel cell. Han in [126] performed the modelling and optimization process to maximize the efficiency of PEMFC. In the study, empirical and semi-empirical models had been used, which covered most of the system components including the stack, humidifier, blower, power converter, and a pump and other balance of plants. This study show that the efficiency gap between the best and worst performance of the system can reach up to 1.2–5.5%, depending on the power load. Reference [134] introduces two mathematical modelling for computing the steady state and dynamic characteristics of PEMFC, including the performance. The study showed that the performance of a fuel cell can be expressed by the voltage-load current (V-I) characteristics, whereby the fuel cell system is divided into three control volumes. From this, a lumped-parameter model for the sub-system can be established using the mass and heat transfer equations. Reference [121] presents simplified PEMFC model for developing cogeneration application. This model uses Annex 42 fuel cell with seven measurable variables to predict power, heat and fuel consumption of a building. In this research work, the proposed cogeneration model was validated by experimental measurements. In reference [135], Mahlia studied and analyzed the feasibility of the fuel cell based system to be used in Malaysia. Reference [136] presents an experimental work where a single tubular solid oxide fuel cell(SOFC) with an electrolyte of stabilized zirconia 8 mol% ceramic powder were used for cogeneration purpose. The study showed the effects of three different fuel flow-rates (174 ml/min, 250 ml/min and 325 ml/min) and two operating temperatures of 650 °C and 75 °C on the output of electrical and thermal powers.

4.6. Hybrid cogeneration prime mover with renewable energy

It is well known that cogeneration can work independently with existing prime mover technology. A step forward, there is also a research that combined multiple prime movers into one configuration. As an example, A. Buonomano in [150] discussed several possible configurations of SOFC with gas turbine. Cogeneration system that combines main prime movers with renewable energy resource has gained interest due to combined advantages of both cogeneration system and distributed energy resources. N. Thilak Raj in reference [24] presented the suitability of integrating renewable energy resources with cogeneration system. This study introduced a novel method, inclusive of comparison with existing designs, modelling and simulation, theoretical and experimental analysis, together with the environmental issues for the renewable energy based cogeneration. The result from the study proved that cogeneration system can be utilized with renewable energy resources to optimize efficiency. Numerous articles that discuss about the hybrid cogeneration system found in the literature. However, it is beyond this article to discuss all of them. Table 4 presents several up-to-date hybrid cogeneration works which include hybrid prime mover and hybrid cogeneration system with renewable resources.

5. Cogeneration control strategy

Since cogeneration has components such as generators, prime movers, distributed resources and load, an efficient control system is needed to ensure the system operate properly to fulfill a demand. Energy management system with well-organized data of each part in the cogeneration system is one example of control method [19]. Energy controlling tool is important to enhance the efficiency of generation process in cogeneration system [19]. According to IEC/ISO 62264 international standard as explained in [65], microgrid control system has five levels: level zero (generation process), level one (the process of sensing and adjusting generation), level two (monitoring and supervising), level three (maintaining and optimizing) and level four (market structure and business model). Meanwhile, the control system for cogeneration based microgrid system has three levels: primary level, secondary level and tertiary level. The principal of these three layer is further categorized as local control, centralized control and decentralized control. This type of control system depends on the size of the microgrid area. L.Meng in [161] described comprehensively the hierarchical control concept of microgrid component. The article explains the concept of hierarchical control system, and the description of control approach for centralized control system. A centralized control consists of power management for microgrid, economic dis-

Table 4
Cogeneration system available in the literatures.

Authors /Year	Combination of prime mover (hybrid cogeneration)								Research interest/Finding	References
	GT	ST	RE	MT	FC	Solar	Wind	Others		
A.Immanuel (2014)	/	/				/			Exergy analysis has been performed to determine the exergetic efficiency of combustor. According to the analysis, it was found that an efficiency was increased from 74.5% to 81.8% as well as steam to air ratio (SAR) was increased from 0.3 to 0.9.	[151]
A.Mundada (2015)					/	/		battery	A quantifying analysis has been performed to observe the economic viability of autonomous systems by assessing the levelized cost of electricity (LCOE).	[152]
Kallol Roy (2014)				/	/	/	/	Diesel, battery	In this study, an energy management system has been proposed to schedule energy generation. Throughout the proposed algorithm, an optimal sizing and operation were obtained. Therefore a developed system can achieve a reliable system in a minimum cost.	[153]
J.Kalina (2011)			/					Biomass	In this work, the investigation of a distributed generation plants that built from gasifier, Internal Combustion Engine (ICE) and Organic Rankine Cycle (ORC) machine as a bottoming unit has been performed. The finding from three different setups show that the total electricity generation efficiency of the plants depended on engine selection and configuration of the systems. The lowest value obtained was 23.6% while the highest was 28.3%.	[154]
S.Obara (2015)					/	/		Flywheel	In this study, a modelling for a cogeneration's equipments has been done using numerical analysis, which consider an energy balance, mass balance and transient characteristics of the equipments. Besides, a fluctuation of the power output of the SOFC and PV as a combined generator has been described. PID controller was used for governor free control and air flow rate control at the SOFC output as well as the fluctuation in PV output was also observed. The finding conclude that load following is difficult to achieve without an inertia system due to the late response of SOFC in the air flow rate control. When the control power fluctuations use a flywheel, the output power is greater than a backup power storage facilities.	[155]
M.Kalantar (2009)				/		/	/	Battery	A development of a supervisory controller to manage standalone system operation has been presented whereby Genetic Algorithm has been used to obtain the optimal sizing and minimum operation cost. In addition, a supervisory control system employing fuzzy logic was designed to manage the maximum energy captured from the wind turbine and solar arrays. The energy generated has been consumed by dump load and stored in the storage.	[108]
A.C.Fereira (2015)			/			/		Stirling engine	In this study, a stirling engines and concentrated solar energy has been used as a heat sources for thermal-economic optimization. Initially, modelling of the components has been done to observe the responses of the system. Besides, regenerator heat transfer, pressure drop and thermal losses has been considered in the thermodynamic analysis. The results of this study shows that implementation of mathematical model reached an optimal solution disclosing a positive annual worth (627 V/year) for the best physical configuration of the system. Also, the best configuration that represents a cogeneration system able to deliver 3.65 kW of electrical power and 11.06 kW of thermal power to fulfill the base heating load of a residential building.	[156]
P.Balcombe (2014)			/			/		Stirling engine battery	In this research, life cycle analysis has been performed to compare the feasibility of developed cogeneration with conventional grid –boiler system. Life cycle assessment has been carried out for these purposes by simulating a daily and seasonal energy demand of different household types. The analysis results showed that the impacts are reduced by 35–100% compared to electricity from the grid and heat from gas boilers. Since no study has investigated integrated PV-SECHP-battery system, the result has been compared individually with those available in the literatures. This gives large rooms for research opportunities in PV-SECHP-battery integration.	[157,158]
S.Pedrazzi (2010)					/		/	Hydrogen	In this study, a complete mathematical modelling and simulation has been presented. A simulations result gave an electrical efficiency and thermal efficiency of 8.2% and 12.5%, respectively. In addition, hydrogen annual surplus of 110.5 kg could be obtained, which can, for instance, be used to feed a hydrogen powered car for about 9500 km.	[159]
G.Prinsloo (2016)					/	/			In this article, a development of hierarchical digital supervisory control for solar powered micro-generation has been presented. Besides, a digital simulation experiments have been conducted to evaluate the operational plans and operational cost of energy management for different storage system. The results showed that an improved energy management efficiency is able to reduce operational cost and customer's energy bill.	[160]

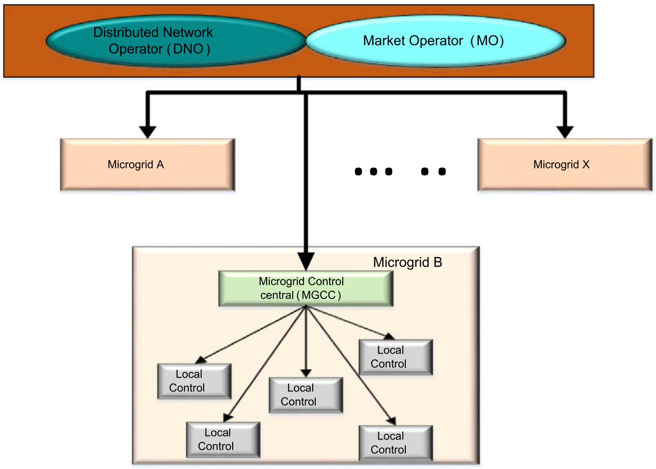

Fig. 15. Links in microgrid centralized control system.

patch, optimization approach and rule based methodology for energy management system. A. M.Bouzid [162] reviewed a control system for a distribute power generation systems, including cogeneration based on renewable energy. The analysis extended the control mechanism that focuses on three topologies, namely grid-forming, grid feeding and grid supporting.

5.1. Local control

Local control is also known as internal control loop target to manage the power of Micro Sources (MS). Basically in microgrid, control starts with the source operating control by the use of power electronics devices, either in current or voltage control modes. At this level of control, the target is to control operating points without any communication system. Also, the local control aims to manage the power electronic interface in voltage and current control mode, as well as to manage the frequency and voltage in the microgrid regardless the system is connected to the grid or standalone. Meanwhile, in current control mode, where the system is often in grid connection mode, the control strategy mainly focuses on management of the active and reactive power. As this is a basic control system, the measured data for local controllers are local voltages and currents, and have simple circuitry and low cost. Most local controllers will exist together with other types of controllers, as majority of microsources require power-electronic interfaces to convert their output to suit with power system specifications. Zheng Zeng in [163] reviewed the topologies and control strategies of multi-functional grid-connected inverters (MFGCIs). In solar photovoltaic, the design, implementation and experimentation of a digital solar controller is usually require Maximum Power Point Tracker (MPPT) command [164]. MPPT is an automatic control algorithm function to adjust the power interfaces and achieve the best possible power harvest, during moment variations of light level, shading, temperature and photovoltaic module. Besides, the aim of the MPPT is to regulate the solar operating voltage close to the maximum power point when it is under atmospheric changes [165]. Presented paper in [20] discussed a proportional integral (PI) control tuning method for cooling the hydrogen production in polymer electrolyte membrane (PEM) fuel cell based cogeneration with 5 kW electrical and 30 kW thermal capacity. In this work, the modelling and control system were designed using MATLAB/Simulink and industrial Programmable Logic Control (PLC). A dynamic control system is introduced in [166] for integrated wind turbine, combining solar photovoltaic as main power resources and diesel generator as a backup system. In this work, MPPT is used to control both solar and wind in order to move the operating voltage close to the maximum power under changing atmosphere conditions. Authors in [167] and [168] studied the MPPT performance for Building Integrated Photovoltaic (BIPV), and described current mode controlled MPPT algorithm including rapid convergence and steady state accuracy. Meanwhile, authors in [169] introduced a dynamic control behavior results of a Doubly-Fed Induction Generator (DFIG) and two other synchronous sources (a diesel and a small hydro-generator) within a microgrid. In this study, the entire load that exceeded the normal power demand of the micro grid internal generation was shed based on the simulation response of the generators upon returning to the pre-overload condition.

5.2. Centralized control

In centralized control, the management of the micro grid is performed by a central controller located at the global control level, known as Microgrid Central Control (MGCC). Normally, a MGCC is available for each microgrid to interface with the Distributed Management System (DMS), therefore the definition of centralization or decentralization is based on the position of the MGCC. Centralized control system is suitable for small sized micro grids as it is feasible to control with the presence of an operator. In order to do a control purpose, variables such as active and reactive power are collected from the Distributed Generators (DGs), Energy Storage System (ESS) and critical loads. At the same time, data about market conditions, security issues and request from upper controls unit are taken into account. This means that a communication network links all the hierarchical control levels. A secondary centralized control compensates the variations of voltage and frequency in primary control level before it proceeds to the tertiary control levels [58,170]. Fig. 15 shows the relationship of each operator in centralized control system developed based on hierarchical controls; designed with added various degrees of intelligence [171]. Many available literature in the references describe about centralized control, for example a series of studies by Dimeas and Hatziargyriou [171–173]. They explained the concept of centralized control by defining the function of distribution network operator (DNO) and market operator (MO). This concept requires a communication link to ensure the information delivered between each segment in microgrid to be successful. The information flow in a centralized control is presented in Fig. 16. Article [174] presents a centralized control consisting of one master controller and several slave controllers for various renewable energy and energy storage system. According to [175], the control level of hierarchical systems can be categorized as Local controllers that consist of Microsources Controllers (MCs) and Load Controllers (LCs), Microgrid Central Controller (MGCCs) and Distribution Management System (DMS). In reference [176], Ali Bidram explained the hierarchical based control system for microgrid, in which a hierarchical supervision with type management and control scheme supported by a communication infrastructure was used to monitor and control the cogeneration system. Antonis in [177] developed an optimization algorithm for low voltage networking application, in which the controller shall optimize the operation of microgrid during the interconnected operation. Reference [178] presents a Distributed Model Predictive Control (DMPC) for efficient management strategy of energy distribution in a

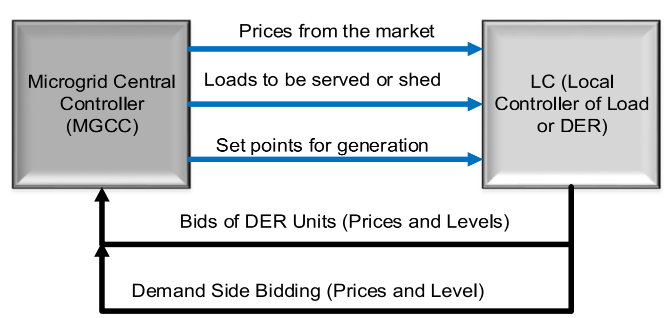

Fig. 16. Information flow in a centralized control system [172].

buildings. Reference [179] presents a centralized control for optimizing nodal voltages of distribution networks in PV-inverters. Control actions are centrally evaluated in real-time by solving a constrained dynamic optimization problem, and aim at minimizing the voltage deviation from a reference value. Another work in [180] proposed a modified central wind farm controller using central control approaches, where active power control problems had been managed using optimization techniques. From the literatures, it can be noted that all microgrid terminals are regulated and managed by the energy control center during communication signal transmission. This will require large size of data center for microgrid with sophisticated operation modes and controllable mode transitions. As a result, the centralized control puts heavy burden to the ECC itself. Hence, centralized control configuration is not suitable for expandable microgrids which have open boundary and huge number of terminals [181]. In order to solve this drawback, a decentralized control system is projected, where the distributed terminals have their own right to make their own decisions based on the local information. The following section explains about the decentralized control system.

5.3. Decentralized control

Since microgrid is a complex and heterogeneous system with diverse controllable devices, a centralized control requires a reliable and high-speed communication network between the central controller and local regulators [182]. Besides, the centralized control structure is not fully compatible with special feature of microgrid which have plug-and-play functionality. Thus, alternative for centralized control by providing decentralized control system is encouraged [183]. The purpose of decentralized control is to specify the maximum power generated by the micro-sources, and at the same time taking into account the capability of micro-grid to support the consumer and increase power export to the grid for market participation. Normally, this type of control is ideally implemented in the microgrid of different suppliers, as there are needs to make separate decision regarding individual situation, besides requiring some micro-grid to function as intelligent control unit. The best characteristic of microgrid that should use the decentralized control method is given in Table 5. Decentralized control system has been used in large number of studies, including conventional decentralized control method by means of voltage/current droop control or voltage/power droop control, for example in articles [175,184,185]. Researchers in [175] performed a control of a single phase ac to dc converter using droop control, while researchers in [184] chose a droop control concept to control the converter. The implementation of droop control was to use the active power “P” as a function of the angular frequency ω and use the reactive power “Q” as a function of the voltage amplitude “E”. Meanwhile in reference [185], a DC link voltage was maintained by droop control, as a function of the expected state of charge (SOC) of the battery. Article [186] presents improvisation of these conventional methods of droop control with the introduction of mode-adaptive decentralized control scheme.

Recently, a decentralized control using a Multi Agent System (MAS) has become a famous approach for supervisory control. Abhilash in [187] reported the application of MAS in the control and operation of microgrids. Dimeas in [188] and [173] described the framework of MAS to solve the control strategy in micro grid system, consisting of four agents: production agent, consumption agent, power system agent and MGCC agent [177]. The procedure to implement the MAS can be found extensively in articles [60,188–194]. Aspects in terms of benefit and drawback of centralized and decentralized control system are given in Table 6.

Table 5
Characteristic of microgrid system suitable for use in decentralized control system.

Each microgrid has different owners, thus a case requiring several decisions should be taken independently and locally.
The operation of microgrid in a market environment requires the action of the controller of each unit participating in the market with certain intelligence.
The local energy sources may have other tasks than only supplying power to the local distribution networks.

5.4. Control strategy for different cogeneration system

Due to factors like size and location of the micro-grid system, each employed control system is different. The load type of cogeneration system also determines how the control strategy should fulfill the system environment efficiently and satisfactorily. Similarly, every cogeneration system is formed by a combination of complicated elements including generators, storage, engine combustor and recuperator. Since they need to provide enough thermal energy to meet many types of industrial process needs, a competence control strategy is necessary to ensure the success of cogeneration system. Control strategy deals with issues that come from several areas including technical areas, time scales and physical levels. In addition, the domain of load power sharing, voltage/frequency and power quality regulation, market participation, short-/long-term scheduling have to be in consideration. As thoroughly discussed in article [161], control strategy of any system in microgrid (or cogeneration) should be designed based on the hierarchical control method, whereby the level of system to be controlled should be recognized. Table 7 presents some control strategies utilized in several cogeneration systems.

6. Cogeneration performance parameters

The performance parameters of cogeneration system are categorized into two parts, which are characteristic of cogeneration candidates and performance parameters of cogeneration plant. In order to fully exploit the cogeneration facility all over the years, the potential candidates of cogeneration system should have several criteria. First, an adequate thermal energy needs must match with the electricity and thermal demand. This is important to ensure both electricity and thermal demands can be fulfilled by the generators. Hence, in the first step of cogeneration system development, the compatibility of any existing thermal system with the proposed cogeneration facility should be determined. Second, a reasonable high electrical load factor or operating hours of the cogeneration system should be recognized. This means that, the duration of electricity and thermal consumption must be well recognized so that the size of cogeneration system developed is worth to support both electrical and thermal demands. Third, a candidate of cogeneration system should have fairly constant and matching electrical and thermal energy demand profiles. In addition, a part of load operation of the cogeneration plant should be avoided because it will give a negative impact to the economic viability of the cogeneration project [71].

There are several cogeneration system parameters that need to be considered before undertaking any economic analysis, which are heat to power ratio, quality of thermal energy needed, electrical and thermal energy demand patterns, fuel availability, required system reliability, local environment regulations, dependency on the local power grid, and option for exporting excess electricity to the grid or to the third party. In comparison with each other, fuel cell prime mover technology has the highest typical power to heat ratio. Also, fuel cell cogeneration system requires 32,000–64,000 h to overhaul. In comparison to other prime movers, fuel cell can reach 55–80% total efficiency. The performance parameters of cogeneration prime movers are summarized in Table 8 [71].

Table 6
Benefits and drawbacks of centralized and decentralized control system.

	Centralized control system	Decentralized control system
Benefits	• Simple implementation • Easy to maintain • Low in cost • Widely used and widely operated worldwide • Has large control over the entire system	• Plug-and-play compatible • Easy to expand • Can avoid single point of failure • Suitable for large scale, complex and heterogeneous systems
Drawbacks	• Has computational burden • Requires large database • Needs high speed bandwidth links • May face single point of failure • Hard to expand • Unfriendly for plug-and-play features	• System needs synchronization between each terminal. • Time consuming for local controller to reach the center control. • Convergence rates can be affected by communication network topology. • High cost needed in the existing control and communication facility. • A distributed location of controllers makes it hard to manage.

7. Application of cogeneration system in commercial building

A cogeneration system can be applied in facilities that need two or more energy uses. Energy uses include electricity, hot water, steam, chilled water, space heating, chemical bath heating, air-conditioning etc. Typically, a building needs electricity and hot water to operate their function. Obviously, electricity has universal use in all buildings, while hot-water applications are more specific for commercial, residential or industrial applications. Steam is used in many facilities to provide space heating, in-process systems, sterilization of instrument, cooking and other applications. The usual uses of heat water from cogeneration system in typical amenities are given in Table 9 [200] while the next subsection presents a detail on cogeneration application in several commercial facilities including airport, hospital and hotel.

7.1. Airport building

Energy consumption in airport building depends on large numbers of factors, since energy demand depends on both structural and operational variables. Structural factors include surface, volume, building orientation, external and roof thermal insulation, while operational variables are number of passengers per year, average occupancy levels in air conditioning areas and seasonal fluctuation. Generally, airport buildings use cogeneration with added cooling function (called trigeneration), which consist of cooling, heating and power technology in a single generation. Fig. 17 shows a basic configuration of this technology, which combines absorbing chillers, auxiliary boiler for cooling and heating function, respectively. Suvarnabhumi Airport in Thailand uses a District Cooling System and Power Plant (DCAP) based on natural gas cogeneration system. The DCAP has been designed to supply electricity, steam and chilled water for heating and cooling purposes for the airport. The controlled temperature in the airport is 24 °C with 50–60% relative humidity, and the cooling network is designed as a radiant floor cooling system. The facility of cogeneration system for this airport consists of two gas turbines, each with capacity of 20 MW electrical output, one steam turbine, two heat recovery steam generators (HRGS) and four auxiliary boilers. The system operates at 8760 h, annually and the electricity generation is around 378,000 MWh annually. Since the electricity demand of this airport is 394,000 MWh annually, extra electricity from the grid is imported to satisfy the requirement [80]. Reference [203] presents the analysis on cogeneration performances against energy consumption by Leonardo da Vinci International Airport (LDVIA) in Rome. LDVIA is Italy's major airport and one of the most important airports in Europe, located in Fiumicino, 28 km from the center of Rome [204]. LDVIA has been equipped with cogeneration system since 2008, along with many of the world's major airports, including Italian Malpensa and Linate airport, the JFK Airport of New York, and Heathrow airport in London. At LDVIA, the electric energy generated to cover electric energy needed is almost entirely self-produced by their own cogeneration system, and only 2% is purchased from external providers. The technical specifications for cogeneration power plant in LVDIA list are thermal power input, effective thermal power available for end user, gross electric power, net electric power, outlet water temperature and inlet water temperature with 57.4 MW_t, 17.8 MW_t, 25.7 MW_e, 25.3 MW_e, 130 °C and 80 °C, respectively. More detailed explanations about the cogeneration system in LVDIA is provided in the reference. Article [205] presents analysis on emission reduction in Istanbul International airport when employing cogeneration system. The study demonstrated the importance of airport developer to choose power and energy generator that can reduce emission level. Articles [206,207] present studies on Malpensa International Airport (MIA) which utilizes cogeneration system for generating power. MIA uses gas turbine cogeneration system with a heat recovery boiler (rated capacity at 20.0 MWe, 28.1 MWt) and absorption chiller at 20.0 MWe. The analysis on both technical and economic viability of cogeneration system in this airport shows that cogeneration system reduces the energy intensity significantly compared to conventional power generation system.

7.2. Hospital building

Hospital is a building with hope. It works around the clock every day, using both electricity and thermal energy. Hospital is a suitable candidate for cogeneration system implementation since it has specific requirement of hospital building such as high space heating demand, year round heating demand for hot water, high power demand, need of backup generators for emergency cases and small plant footprint to give more space for treating patients [208]. Hospitals are perfect candidate to implement cogeneration system since they utilize both electrical and thermal energy in their services. In Europe, there are hospital buildings that implement cogeneration system to fulfill their load demand. There are also numerous research studies on the implementation of cogeneration system in order to improve the existing cogeneration system in hospitals [209]. Alfredo in [87] discussed the energetic and economic benefits generated by cogeneration system installed in hospital building. There are various cogeneration topologies employed in hospital building, but all have general configuration as shown in Fig. 18. Previously, most hospitals cogeneration system use gas and steam combustion in their cogeneration system. Before, utilizing fuel cell has limited capability, but now they have move forward to employ fuel cell as a prime mover in their cogeneration system.

Several research studies presented the utilization of fuel cell in hospitals, due to the benefits of fuel cell, such as able to reduce onsite emissions directly, environmental friendly, able to provide energy services for that site, compact, silent and clean. Thomas in [211] described the advantages of integrating the fuel cell in hospital power supply together with examples of hospital site that use fuel cell in their cogeneration system. Kaiser Foundation Hospitals has agreed with the Southern California Gas Company as partner to test the reliability and

Table 7
Type of control system for different cogeneration in literatures.

Authors /Year	Type of cogeneration system						Control system approach	Articles
	GT	ST	RE	MT	FC	Hyb		
M.Kalantar (2009)				/			A supervisory control system has been developed to manage the system operation. Genetic Algorithm is used to obtain optimal sizing and minimum operation cost.	[108]
A.Cagnano (2015)						/	A centralized voltage control scheme has been designed to control a grid-connected photovoltaic plant. The proposed control system has been tested on a typical medium voltage distribution network.	[179]
P.Garcia (2014)					/	PV WT	An energy management system based on adaptive neuro-fuzzy inference system has been developed to control the entire system. The result shows that the improved system gives better and more reliable performance compared to traditional PI controller.	[195]
Xiao Wu (2016)	/						A predictive control approach has been used to control a 80 kW micro gas turbine, in which the result shows improvement in operation performance.	[196]
A.P. Wiese (2015)	/						An experiment work of a fully nonlinear model predictive control has been performed for a gas turbine cogeneration system. Initially, the formulation of model predictive control has been modelled to minimize output tracking error. Furthermore, a controller performance has been evaluated by regulation experiments.	[197]
S.Semprini (2016)	/					PV	A control approach has been performed based on three operation strategy. First, fuel have been supplied to ensure the system output maintained at rated value during sun hours. Second, fuel was supplied to ensure the overall efficiency always above a certain minimum value. Third, the system was assumed to work at full capacity from 7 a.m. to 11 p.m. during working hours. First control approach shows a good performance in terms of fuel supplied to the system.	[198]
M.Mokhtar (2012)						/	Multi agent system control based for efficient energy has been used to control energy flow in building. Simulation results proved that the control approach gives better energy control and thermal comfort.	[193]
V.Dash (2015)						/	A control algorithm has been proposed to obtain the power management for hybrid cogeneration system. The control algorithm diverts the excess PV power into the electrolyzer when battery reaches 99.5% to protect the battery from overcharging. In this control strategy, the dump load can be eliminated by limiting the power drawn from the sources, to match the load requirements.	[118]
S.Kohsri (2011)					/	/	A control and monitoring approach has been constructed in Labview software, where the main central control system requires data from the remote energy system. The data needed include power generation, load consumption and control parameters.	[199]

Table 8
Cogeneration size, cost and performance parameters.

Characteristic	Technology	Steam turbine	Gas turbine	Microturbine	Reciprocate engine	Fuel cell
Cost [26,200,201]	Installation cost ($/kW)	670–1100	1200–3300	2500–4300	1500–2900	5000–6500
	O & M costs ($/kW)	0.006 to 0.01	0.009 to 0.013	0.009–0.013	0.009–0.025	0.032–0.038
Size [116,202]	Capacities	500 kW to 80 MW	250 kW- 200 MW	20–250 kW	20 kW- MW	0–83.6 MW
Performance parameters [26,202]	Electric efficiency (%)	5–40%	24–36%	22–28%	27–41%	30–63%
	Overall efficiency (%)	Near to 80%	66–71%	63–70%	77–80%	55–80%
	Effective electrical efficiency	75–77%	50–62%	49–57%	75–80%	55–80%
	Typical power to heat ratio	0.07–0.1	0.6–1.1	0.5–0.7	0.5–1.2	1–2
	Part-load	ok	poor	ok	ok	good
	Hours to overhaul (hour)	> 50,000	25,000–50,000	40,000–80,000	30,000–60,000	32,000–64,000
	Availability	72–99%	93 – 96%	98–99%	96 – 98%	> 95%
	Start-up time	1 h to 1 day	10 min to 1 day	60 s	10 s	3 h to 2 days
	Power density (kW/m2)	> 100	20–500	5–70	35–50	5–20
	Fuel pressure (psig)	n/a	100–500 (compressor)	50–140 (compressor)	Nil	Nil
	Fuels	All	Natural gas, synthetic gas, landfill gas and oil fuel	Natural gas, sour gas, liquid fuels	Natural gas, biogas, LPG, sour gas, industrial manufactured gas	Hydrogen, natural gas, propane, methanol
	Uses for thermal output	Processed steam, district heating, hot water, chilled water	Heat, hot water, low power and high power steam	Hot water, chiller and heating	Space heating, hot water, cooling and low power steam	Hot water, low power and high power

Table 9
Water heating from cogeneration development utilization in several public amenities.

Amenities	Water heating application
Restaurants	Kitchen services for dishwashing, lavatory hot water
Hotels	Guest room water for bathing and showering, laundry service, kitchen service for dish washing, swimming pool heating, spa heating
Health and fitness center	Swimming pool heating, spa heating, showers and lavatory services
Municipalities	Swimming pool heating, spa heating, lavatory and shower services
Hospital	Patient room bathing and showering, therapeutic pools, spa, swimming pools, kitchen service, laundry
Recreational pool	Swimming pool heating, water slide areas, tubing and wave riding water heating, shower, lavatory services
Nursing homes and care services	Patient room showering and bathing, therapeutic pools, spas, kitchen and laundry
Coin operated laundries	Hot water for laundry
Metal plating factories	Hot chemical bath
Residential	Swimming pool heating, spa heating, lavatory water for bathing and showering, kitchen and laundry
Food processing plant	Hot water for cooking, cleaning dishes, lavatory services

feasibility of fuel cell to power hospitals. Their initial plan was to install four 200 kW acid phosphoric fuel cells at three hospitals in order to improve power quality, energy security, reduce on-site emission and financial savings. There are also hospitals that currently use hybrid cogeneration in their system. Kow Loon Hospital in Hong Kong operates by hybrid cogeneration system, utilizing grid-connected hybrid solar, and wind turbine combined with conventional boiler system. The installed system consists of 108 solar photovoltaic panels and 2 Vertical-Axis Wind Turbines (VAWT). The system fully takes advantage of solar and wind power to generate electricity, whose annual energy output is about 29,000 kWh, and able to reduce around 22,620 kg of Carbon Dioxide [212]. However, when there is neither sun nor wind, the hospital will draw electricity from Hong Kong's conventional power grid in order to maintain the power supply. The installed photovoltaic panels and VAWT are arranged to fully utilize the roof space, as illustrated in Fig. 19.

North Country Hospital in Newport utilizes biomass cogeneration system to fulfill their load demand. It is typical in rural general hospitals across America to have 25 beds for internal patient care, an emergency room, a dialysis unit and critical outpatient services in an area of 121,000 square feet [213]. The steam produced from biomass boiler can be used for all purposes similar to fossil fuel boiler, such as providing heat, domestic hot water, sterilization, laundry, heat for absorption chilling and power production by steam turbine and generator. The recovered heat is used for space heating, cooling, cooking, cleaning or other uses. Fig. 20 shows a biomass cogeneration plant implemented in this hospital.

Renedo in [214] studied different cogeneration alternatives for University Hospital in Spain by analyzing different possibilities for providing heating, air conditioning and hot tap water to a hospital center. In order to this, two types of cogenerations system are considered, one with diesel engines and another one with gas turbines. For each method, two different control strategies were studied in order to maximize the electrical production and to maximize the time of use at full load. Also, the study proposed a solution to reduce emission of CO_2. In [215], C.J Renedo analyzed different alternatives to provide energy to hospitals. This study considered several power sizes and control strategies for diesel engines and gas turbines, whose result show that the options with diesel engines are more efficient compared to the ones with gas turbines. A study on conventional cogeneration system in Tzaneio Hospital in Greece is described in reference [216]. The system uses two large boilers, each with a rated power of

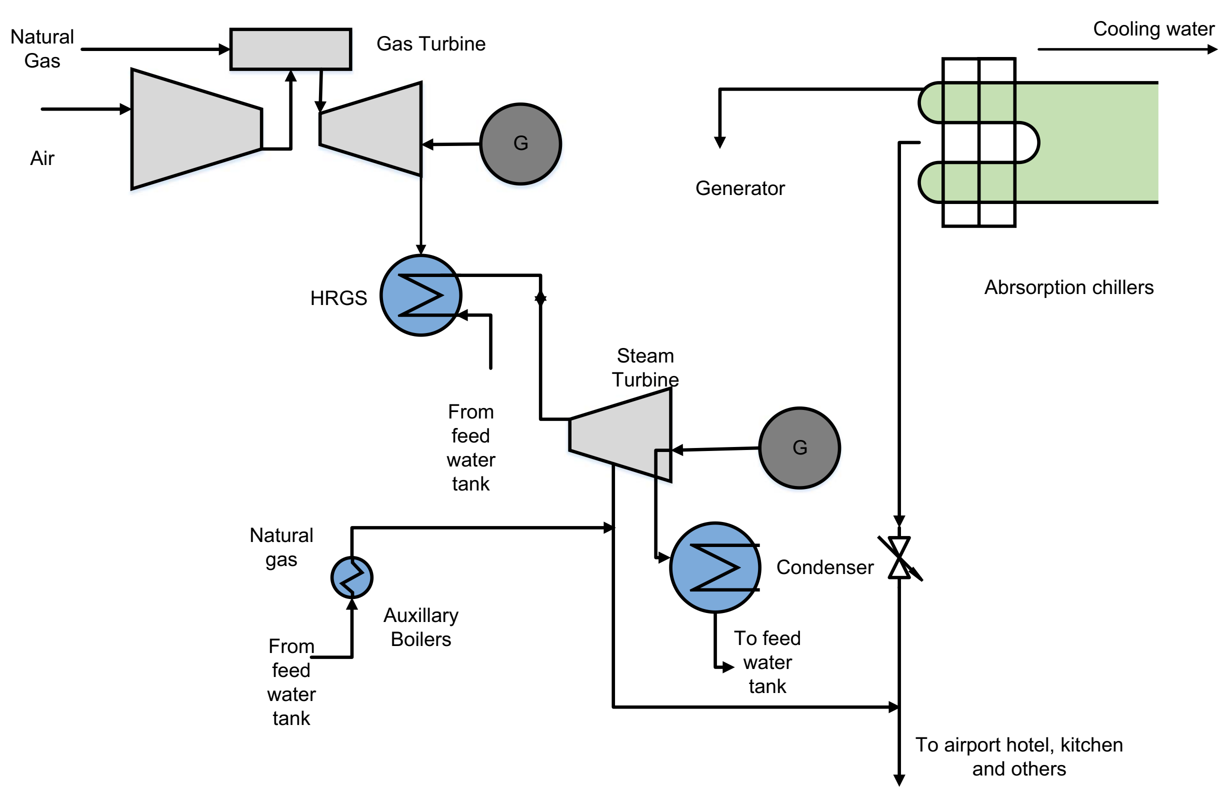

Fig. 17. General cogeneration system in airport building.

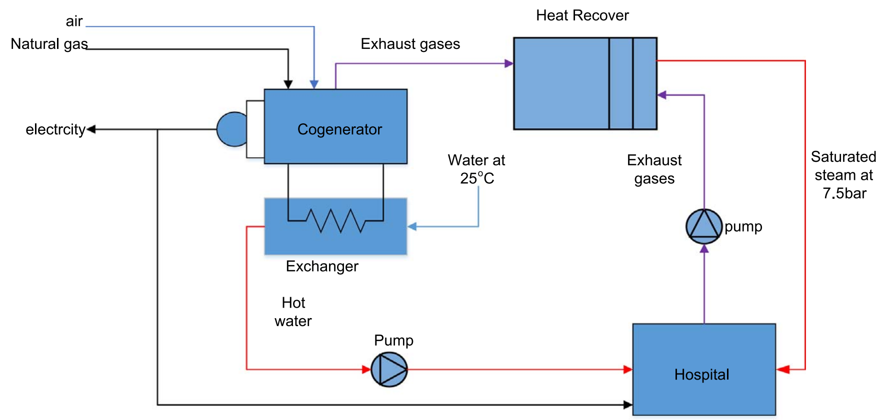

Fig. 18. General configuration of cogeneration system installed in hospital building [210].

Fig. 19. Photovoltaic panel and VAWT installed at the roof of Kow Loon Hospital, Hong Kong [212].

Fig. 20. Biomass-cogeneration plant in North Country Hospital [213].

10,00,000 kcal/h, and two smaller boilers with capacity of 750,000 kcal/h each. The steam generators operate by natural gas and have a total steam production of 2000 kg/h. The exhaust gases are passed in through a central chimney. The exhausted steam boiler is used for water heating, and in the form of steam, it will be used for washing machines, sterilization, operating rooms and kitchen facilities. The natural diesel gas engine operates for 8000 h/year and the backup unit operates for 5000 h /year, thus the developed cogeneration is indeed economically profitable. The analysis also considered the value of Benefit Cost Ratio (BCR), Internal Rate Return (IRR) and Net Present Value (NPV) for lifetime of 20 years. Article [210] presents a thermodynamics and thermo economic study for Hospital de Clinicas Barao Geraldo, in which the second law of thermodynamic was used to analyze the cogeneration system. The hospital under study uses alternative internal combustion engine (AICE) to fulfill their demand. The analysis was based on four scenarios which correspond to cogeneration technologies. The finding showed that the most efficient plant is the cogeneration plant that associate AICE with double effect absorption machine, which has the possibility to achieve a global efficiency around 58%. Reference [124] presents a techno-economic analysis for the installation of hybrid cogeneration consisting of photovoltaic, battery and fuel cell in hospitals in Malaysia. Throughout the simulation analysis using HOMER environment, the proposed cogeneration system projected the lowest TNPC, LCOE and operating cost which are $ 106,551, 0.091 $/kWh and 7245 $/year, respectively. Besides, the proposed cogeneration system had been proven environmentally friendly as it would only produce total of 25,873 kg/year of pollutant gas. Another work on cogeneration system for hospital located in south of Italy is presented in [217]. The proposed work had been tested through experimental dataset using real thermal and electric consumption data. The results showed that the energy performance could significantly increase to 20% with optimal sizing and time planning of cogeneration system compared to a plant that does not adopt any cogeneration system.

7.3. Hotel building

Hotel is a commercial building that contributes to a country's economy through the tourism activity. The energy consumption in the hotel would significantly affect the level of greenhouse emissions. Cogeneration system is an alternative to the solution, as it can assist hotel owners to produce their energy for internal use. The literature shows that there are many types of cogeneration system utilized in hotel building. However, it is beyond this study to discuss all of them in this article. In reference [218], Hotel Icon located in Hong Kong was used as a case study to observe the viability of fuel cell based cogeneration system. Hotel ICON consumed 12.26 GWh electricity in year 2012; in total consuming US$1.44M. To overcome this situation, a cogeneration system based on SOFC was proposed, since the study focused on a large scale application instead of single family use. The cogeneration suggested in this work consisted of five units of SOFC, model 200 kW ES-5700. In the configuration, if the electrical energy demand exceeded the SOFC capacity, they would be complemented by the grid supply. The analysis also considered the benefits in economical view which would give payback in 10 years. Meanwhile, technical analysis showed increment of efficiency from 84% to 94%. Also, the researcher suggested the implementation of trigeneration in the hotel building to improve energy saving in the building. J.R Galvão in [219] selected Marvão Castle hotel in Portugal as a case study. The hotel uses two combustion engines, one is a boiler for hot water and the second is an emergency engine used to supply electricity. The hybrid cogeneration consists of gas turbine, biomass and solar to generate energy, which had been analyzed experimentally. The analysis proved that hybrid cogeneration is technically reliable and economical solution, which also offers efficient energy consumption and low emission level. A photovoltaic source for the energy model added to the main

cogeneration system would supply additional electrical energy at peaks periods, while excess energy would be sold at price of 0.6175 €/kWh$_e$. Although the PV panels generally produce 7.22% of electricity the whole year around, during the months of July and August, the PV panels can produce more than 8.23%. Article [220] presents an optimization study for large scale hotel that combinations fuel cell, wind and solar in their power generation system. The hotel site is located in south eastern of Queensland, Australia, with annual energy consumption of 5.5 GWh, with an average energy consumption of 15,000 kWh/day. Peak load for the year is 966 kW. The finding from optimization analysis through HOMER software showed that hybrid cogeneration with PV and wind resulted in a competitive NPC, thus a negative GHG emission in total, facilitated through sale of excess electricity to the grid. Amir in [75] performed an analysis on three types of cogeneration technology comprising of micro turbines, internal combustion engines and fuel cell with solar and conventional sources, to meet the demand of hotel complex located in Coimbra, Portugal. The study used both photovoltaic and solar thermal for electricity generation, while the micro turbines cogeneration systems operated by producing high-energy gas stream run by electrical generator. The internal combustion engine and SOFC operated by electrochemical process, utilizing natural gas to produce electricity and thermal energy. The finding showed that combination of cogeneration and renewable energy can give substantial impact to the technical and economical aspect of energy generation. Mahesh in [221] conducted thermodynamic and economic analysis of diesel cogeneration and trigeneration. The system under study consisted of diesel generator, exhaust heat recovery unit, thermal stabilizers, auxiliary boiler and absorption chiller to supply a typical 100-room hotel in India. Thermodynamic analysis was formulated in the system, taking into account the basis of first law of thermodynamics. The selection of diesel generator in the measurement and analysis for auxiliary boiler and chiller would maximize the fuel savings and reduce cost.

7.4. Other buildings

Cogeneration system is also being used in various types of building, including supermarkets, educational institutions, office buildings and residential. The current trend now is to employ hybrid cogeneration to boost the benefits for existing system. Table 10 presents several researches on cogeneration system application in other types of commercial buildings including general building, residential or house and shopping complex.

8. Discussion on cogeneration issues

This section discusses some important issues that need to be highlighted in developing cogeneration system based on the review on the aspects of cogeneration system from technical point of view.

8.1. Factors that influence the cogeneration choices

Several factors like cogeneration size, electrical-thermal requirement, prime movers selection and financial cost influence the selection of cogeneration system the most. In reality, there are several factors that influence the decision to choose cogeneration type. The first factor is the base electrical load matching, where the cogeneration plant is sized to meet the minimum electricity demand of the site based on the historical demand curve. The rest of the required power is purchased from the utility grid. The site thermal energy requirement could be met by the cogeneration system alone or by additional boiler. If the thermal energy generated by the base electrical load exceeds the plant's demand and if the situation allows, excess thermal energy can be exported to the neighboring clients [74]. The second factor is the base thermal load matching, where the cogeneration system is sized to supply the minimum thermal energy of the site. Stand-by boilers or burners will run when the demand of heat is high. The installed prime mover will be operated at full load at all times, if the electricity demand of the site exceeds capability. The third factor is the selection of prime mover, where gas turbines and reciprocating engines will recover exhaust heat in the form of steam or hot water. There are various uses of recovered heat in hospital buildings, such as space heating, domestic water heating and pool heating. In addition, the steam or hot water also can be used by fire absorption chillers to supply chilled water for hospital space conditioning. Steam can also be used for sterilization purpose. Another factor is financial issues, because cogeneration systems are generally expensive to install. The installation cost ranges from $1200 (RM3600)/kW, and up to $1900 (RM5700)/kW. The cost may increase due to design enhancement, because of the building configuration for housing the cogeneration system, and the inclusion of thermal-end use equipment, such as temperature controlled heat exchangers and absorption chillers. In addition, the installation cost is also affected by site condition, if it is able to permit electrical and fuel interconnection cost.

8.2. Installing a cogeneration plant

Engineers and project planners will need to investigate the plant development beforehand, in terms of financial aspect, because this is important for the suitability of plant location in the next procedure. This is vital to ensure that there will be no practical obstacle that cannot be overcome as part of the normal cogeneration design and development process. Besides, early optimum consideration on the selected location will avoid excessive costs. In this manner, the plant needs to be sited in a location where it can remain for a long period without disruption or obstruction, either initially or in future. The potential location also should have sufficient space to allow access for maintenance and to house auxiliary equipment. Since cogeneration plant must be connected to the existing site, they require some modifications of utility connections. Therefore, they will need to be accessed for storing additional fuel, water and other related things. Development and implementation of cogeneration system will produce long-term noise because of continuous operation. Due to this condition, the location selected should have minimum impact of noise.

8.3. Financial evaluation and investment for cogeneration system

Further development of the cogeneration system needs to acknowledge the existing technical aspect of the system. Financial assessment throughout the life cycle of the project also must be evaluated. The owner of cogeneration project needs to consider the initial investment, including the cost of re-engineering and planning. The plant owner has to know the requirement of the plant. If the cogeneration equipment needs to be imported, the prevailing taxes and duties of the equipment cost should be added. On the other hand, if the system owner plans to purchase cogeneration equipment from different supplier and then assemble them on site, the cost of preparing the site for civil, mechanical and electrical work such as electrical connections, piping of hot and cold utilities, instrumentation and control must be taken into account. Moreover, if the planner wants to adopt a cogeneration system as a retrofit at an existing site, the cost of item will greatly depend on the existing facilities, either to replace or upgrade. The installation of cogeneration system by integrating the plant into existing setup may lead to decrement in economic evaluation. Here, the cost associated with such losses has to be included in the total project cost. The cost analysis for annual cost should also include the insurance fees and properties taxes. In addition, the operating and maintenance costs should include the direct and indirect cost of operating new cogeneration facilities like equipment overhauls and replacement of parts. Fuel cost will give significant impact to the development of the cogeneration system. Hence, to estimate the results of cogeneration system payback in profit, the analysis of net present

Table 10
Application of cogeneration system in others commercial buildings.

Type of building	Type of cogeneration	Findings	References
General buildings	Hybrid fuel cell, micro turbine, photovoltaic.	An energy saving has been improved and it also reduce an operational cost of the designed system.	[13]
	Hybrid hydrogen, SOFC, gas turbine and generator heat exchanger	An exergy efficiencies in the system has been increased with addition of external parameter. Hybrid cogeneration which combined hydrogen, SOFC, gas turbine and generator heat exchanger give an optimal cost.	[222]
	Hybrid solar thermal, PV and micro CHP	In this study, a calculation of primary energy consumption and emissions inclusion of Life Cycle Cost analysis has been performed. The results show that the primary energy consumption of the proposed design is lower than the conventional case.	[223]
	Gas turbine	Application of gas turbine cogeneration in two type of building had shown an increment in system efficiency, mass balance and energy balance while the thermodynamic properties and emission has been reduced.	[80]
	Hybrid solar and fuel cell	In this article, three operation of SOFC and PV system has been analyzed and compared. The operation of single SOFC gave 83.6% efficiency compared to others combination.	[224]
Residential/ houses	Gas engine and waste-heat boiler (GE/ WHB) unit	This study has been performed to evaluate the energy savings that can be achieved by adoption of the cogeneration system for eight apartments in residential areas. The area of studied apartments are in range of 57200 m^2 to 182760 m^2. The results obtained shows that more than 30% energy save for natural gas based cogeneration system.	[225]
	Micro CHP (fuel cell)	In this study, a micro CHP has been developed for a residential. The analysis for thermal storage and thermal load has been accomplished by the hydraulic process. The results show that the cogeneration can increase the system balance.	[226]
	Stirling engine	In this study, an experimental and a numerical analysis of a commercial stirling unit for 8 kW of hot water and 1 kW electricity has been performed. The analysis for stirling unit have shown an increment in electric efficiency and thermal efficiency of 9% and 90%, respectively.	[100]
	Hybrid Fuel cell, photovoltaic, hydrogen, PHEV	In this article, a hub model for residential has been presented. This hub is able to receive electricity, natural gas and solar radiation at its input port to supply essential electrical, heating and cooling demands at the output port. In order to achieve the target, an optimization problem has been formulated and solved for three different case studies with objective function of minimizing total energy cost. The results gave a cost saving up to 40% and multi-optimization result a reduction in emission level.	[227]
	Natural gas-fuelled internal combustion engine	In this study, a system consist of a natural gas-fuelled internal combustion engine cogeneration unit with 6.0 kW has been presented. The finding from simulation showed that the proposed system made was possible to reduce the primary energy consumption, the equivalent carbon dioxide emissions and reduce the operating costs with respect to the reference system. The system offered 6.5% energy demand saving, 12.2% reduction in emissions and 20.5% reduction in operating cost.	[228]
Shopping complex	Hybrid CHP-CCHP, solar photovoltaic and solar thermal	In this study, the effectiveness and flexibility of modelling approach for the analysis, design, and ongoing assessment of new DER technologies under changing market conditions has been validated. The result show that the system had produced a system balance and it offers 94% balance in cost and 50% reduction in emissions.	[229]
	Natural gas	An evaluation against a factors that can give an impact to the installation of cogeneration system in a shopping complex has been studied. Besides, a technical visit to two shopping malls in Rio de Janeiro, Brazil had pointed out that factors of system capacity and reliability of energy supply contributed to use natural gas cogeneration system in the shopping complex.	[230]
	Natural gas fired	In this study, the technical and economic potential of natural gas fired cogeneration system for mall in Brazil has been identified throughout the use of an assessment model. The analysis from an economics study proved that the system with ROI under 25% require the support from the policies maker.	[231]

value (NPV) is normally performed. In NPV analysis, investment decision will be made based on the financial indicators calculated from the cash flow stream. The estimation on profit payback from the cogeneration system will help the project owner to minimize risk. A sensitivity analysis can also been done to observe the initial and future condition of potential cogeneration plant system.

8.4. Potential risk in development of cogeneration system

Integration of cogeneration project into existing power generation plant will pose several risks to the entire system runner. There are five categories of risks that may happen: construction, operation, fuel supply, off-take and political. In construction risk categories, the issues that may occur are regarding to time, cost, technology and quality of the project. Certified engineer and engineering workers with related experience can help to overcome this problem. Operation risk may happen due to the maintenance of the performance levels and cost of constraint. Experienced operators can help to monitor system performance. Cogeneration system that operates based on the availability of fuel source will have to make sure fuel availability, because fuels like natural gas, water and diesel should be maintained in certain specific amount with reliable prices. The off-take risks include quantity of energy produced, capacity of charge, base unit price, and term of contract. Besides these, political risks can affect the cogeneration system development, including the legislation, taxation and environmental controls. The project have to fulfill the requirement ruled by the stakeholder, while making sure the implementation of cogeneration plant is permitted and provide a huge benefit to the society.

9. Challenges and future prospects

Cogeneration technology that offers high efficiency in the transformation of energy with minimum environmental pollution comes with several challenges. In order to reap the maximum benefit from this system, several efforts have to be in account. First, it needs to have the right size, especially the size of the generator. Proper size will produce the right amount of energy to supply load with minimum losses. In this case, equipment modelling is an important exercise for cogeneration

optimization. In practical point of view, cogeneration configuration size depends on the site condition and requirement. From economic view, cogeneration plants are more sensitive to changeable input parameters compared to classical separate heat and power generation. This is because cogeneration plants are more complex in terms of process configuration, products costs and values of electricity, steam, hot water and chilled water. For example, implementing cogeneration system at a hospital facility will present other challenges in terms of system sizing and equipment selection, economic strategies, financing, site, electrical and thermal design conditions, pollutant emission and government-permitted policies.

The selection of prime movers type for a developed cogeneration system will also be a tough challenge. This is because prime movers suitable for the plant requirement can only permit certain maximum energy production to fulfill the load demand. In order to choose the best prime movers for cogeneration plant, several factors have to be taken into account such as performance of prime movers, electrical and thermal design conditions, air emissions reduction, electrical utility interface, gas utility interface, operations and maintenance, and project risk mitigation system. Among all prime movers types, fuel cell seems to be most promising technology as they can suit many types of load profile, either in stationary or mobile applications. Fuel cells have the potential for use in traditional technologies in various markets, as their size ranges from very small batteries and sensors up to multi-megawatt power plants. However, one of the challenges in transforming the market of fuel cells is the lack of information on lifecycle and emissions. Therefore, analytical and numerical analyses have to be done to ensure the suitability of prime mover with the power plant.

Control system for the cogeneration is another crucial technical challenge. The recognition of control types such as centralized, decentralized and local controls to control the developed system is necessary before the overall system can operate well. For example, in industrial process, special control procedure is needed to perform industrial automation. Industrial automation can be defined as all automatically executed actions to guarantee industrial production system to operate in desired operating conditions and fulfill desired tasks. The operation take into account suitable programmable logic control (PLC) and Supervisory Control and Data Acquisition (SCADA) programs, conventional control tasks (e.g. feedback control), as well as complex control procedures.

The next challenge is the implementation of economic strategies, as financial support is the key of successful system. A cogeneration system must aim to get the profit payback, to cover the cost of maintenance as well as support fuel cost. Selection of the most appropriate method for financing the project depends on the state of the company's profile, degree of risk and benefits associated with the project. Hence, economic investigation is a must, normally analyzed using net present value (NPV) to estimate the investment profit.

The challenges in developing a cogeneration system offer research opportunities in area of system sizing and equipment selection, control system, economic strategies, and contract for system installation. This is due to reason that no technology will remain static solely for technologies that are still in early stage like cogeneration system. Cogeneration is still in its early age because their application is still new in major companies, especially in Asia. Nevertheless, expanding the cogeneration system in a future still has a positive prospect. Modern control systems currently ongoing processes are mostly designed to integrate renewable energy resources into the grid. Because of the aging factors in equipment installation, transformation from conventional grid to more intelligent grid requires more development on cogeneration system in urban and rural building. By implementing the cogenerations system, people can save more in terms of expenditure. In fact, with certain regulations provided by the government, cogeneration project owners can gain additional profit from the incentive provided. Moreover, the support from the stake holder will ease the installation and implementation of cogeneration.

10. Conclusion

This paper has comprehensively reviewed cogeneration system that can be adapted into microgrid. This paper starts by explaining the concept of smart grid, microgrid and cogeneration system, followed by the principle operation of cogeneration. Compared to traditional grid, smart grid has extra benefits, including digital structure, two-way communication, distributed generation, numerous sensors and smart meter, remote checks and control, pervasive control and more customers. Also, smart grid can perform self-healing and self-monitoring function. Microgrid that adapts the features of smart grid but operated with lower level voltage is more efficient and manageable. This study proposes microgrid configuration, whose energy resources system, energy storage system and loads are designed according to various suitable topologies to fulfill all load requirements. Several standards such as IEC 61970,61970, IEC 61850,61850, IEEE P2030 and ANSI C12.18 are outlined as guide for practical implementation of microgrid. Among all topologies in microgrid, cogeneration is the most efficient way to produce and manipulate energy. In cogeneration system technology, both thermal and electricity can be generated simultaneously using single fuel, with efficiency up to 85%. Compared to traditional power generation, cogeneration system is more prominent as it is more efficient, able to reduce an energy cost, able to predict uncertain electricity price, can reduce air pollutant and able to enhance the reliability of power system. Due to these benefits, cogeneration is widely implemented in buildings like hotels, hospitals, education buildings and industrial buildings. Prime movers in cogeneration system are gas turbine, steam turbine, micro turbine, reciprocate engine and fuel cell. Among all, fuel cell is the most promising technology since it has most efficient performance, with 55–80%, compared to others. In addition, fuel cell has the flexibility in terms of fuel resources as it can come from hydrogen, natural gas, propane and methanol. This paper also presents the performance parameter for each prime mover, including power to heat ratio, part load, hours to overhaul, start-up time and power density. Since cogeneration has similar concept with microgrid, it requires a sophisticated control system to manage its operation. Thus, cogeneration employs a hierarchical control system consisting of three types of control; local control, centralized and decentralized control. Each control methodology has to consider the requirement of plant besides fulfilling the demand. This paper has also described two types of performance parameters of cogeneration that influence the efficiency of the system, which are characteristic of cogeneration candidates and performance parameters of cogeneration plant. In addition, since cogeneration uses a single process to generate both electricity and usable heat or cooling, the appropriate size for the proportions of heat and power needed is vary from site to site, so the type of plant must be selected carefully and appropriate operating schemes must be established to match demands as closely as possible. Since cogeneration system is suitable to be implemented in many types of building, a review on the application in commercial building has been included. The effectiveness of cogeneration system in real situation has been studied by observing several case studies in commercial buildings including airport, hospital and hotel. Majority of the researches employed renewable energy combined with cogeneration prime mover to obtain maximum benefits from the desired system. Various designs, prime movers performance, and economic and environmental aspects have been observed in each case study. This paper will be useful for researchers in cogeneration technologies as guide to make effective decisions, as well as generate more ideas in application of cogeneration in modern micro grid power system.

Acknowledgement

The authors would like to express gratitude to Ministry of Higher Education Malaysia (MOHE) for financial support and Universiti

Teknologi Malaysia (UTM) for providing comprehensive library facilities. Funding provided by fundamental research grant scheme (FRGS) under vote 4F596 and long term research grant (LRGS) under vote RJ130000.7823.4L818, Universiti Teknologi Malaysia (UTM) are also greatly appreciated. Lastly, thanks to colleagues who have either directly or indirectly contributed to the completion of this work.

References

[1] Law P. Public Law 95-95 95th Congress An Act, 1976, 1; 1977.
[2] Weisenmiller RB. et al. Energy Aware Planning Guide; 2011.
[3] Markovic DS, Zivkovic D, Branovic I, Popovic R, Cvetkovic D. Smart power grid and cloud computing. Renew Sustain Energy Rev 2013;24:566–77.
[4] Isa NM, Tan CW, Yatim AHM. Smart Grid Technology: Communications, Power Electronics and Control System, in *2015 International Conference on Sustainable Enegy Engineering and Application(ICSEEA)*; 2015, p. 10–14.
[5] Zahedi A. Smart Grid; 2011.
[6] Anda M, Temmen J. Smart metering for residential energy efficiency: the use of community based social marketing for behavioural change and smart grid introduction. Renew Energy 2013;67:119–27.
[7] Peng L, Yan G. Energy Procedia Clean Energy Grid-Connected Technology Based on Smart Grid; 2011.
[8] Gardiner BB. Can smart grid solve all of our energy problems ? Smart Grid, no. March 2013; 2015. p. 8349.
[9] Wang W, Xu Y, Khanna M. A survey on the communication architectures in smart grid. Comput Netw 2011;55(15):3604–29.
[10] DEsigning Sustainable On-site CHP Systems, *ASHRAE Meet*., no. Lcc; 2007.
[11] Frangopoulos CA, Lygeros AI, Markou CT, Kaloritis P. Thermoeconomic operation optimization of the hellenic aspropyrgos refinery combined-cycle cogeneration system. Appl Therm Eng 1996;16(12):949–58.
[12] Hawkes ADÃ, Leach MA. Cost-effective operating strategy for residential micro-combined heat and power, 32; 2007. p. 711–723.
[13] Medrano M, Brouwer J, McDonell V, Mauzey J, Samuelsen S. Integration of distributed generation systems into generic types of commercial buildings in California. Energy Build 2008;40(4):537–48.
[14] Li Z, Reynolds A, Boyle F. Domestic integration of micro-renewable electricity generation in Ireland – The current status and economic reality. Renew Energy 2014;64:244–54.
[15] Gu W, et al. Electrical power and energy systems modeling, planning and optimal energy management of combined cooling, heating and power microgrid: a review. Int J Electr Power Energy Syst 2014;54:26–37.
[16] Mohamed AR, Teong LK. Energy Policy for Sustainable Development in Malaysia, Jt. Int. Conf. Sustainable Energy Environ. (SEE), 28, no. December 2004; 2010. p. 940–944.
[17] Chua SC, Oh TH. Review on Malaysia's national energy developments: key policies, agencies, programmes and international involvements. Renew Sustain Energy Rev 2010;14(9):2916–25.
[18] Cavalcante CAV, Lopes RS. Multi-criteria model to support the de fi nition of opportunistic maintenance policy: a study in a cogeneration system. Energy 2015;80:32–40.
[19] Schellong W, Energy controlling for cogeneration systems in municipal utilities, *2013 International Conference Clean Electr. Power*; Jun. 2013. p. 280–287.
[20] Sağlam G, Tutum CC, Kurtulan S. A new PI tuning method for an industrial process: a case study from a micro-cogeneration system. Energy Convers Manag 2013;67:226–39.
[21] Kaviri AG, Jafar MNM, Tholudin ML, Avval HB. Exergy analysis of a Cogeneration Heat and Power (CHP) system (first and second law analysis), in 2011 IEEE 1st Conference on Clean Energy and Technology, CET 2011; 2011. p. 29–33.
[22] Haeseldonckx D, Peeters L, Helsen L, D'haeseleer W. The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO_2 emissions. Renew Sustain Energy Rev 2007;11(6):1227–43.
[23] Shams S, Ahmadian J, Ghorbanian MJ. Applying the CHP Method on Small-Scale On-site Power Generation; 2013. p. 303–306.
[24] Raj NT, Iniyan S, Goic R. A review of renewable energy based cogeneration technologies. Renew Sustain Energy Rev 2011;15(8):3640–8.
[25] Gu W, Wu Z, Yuan X. Microgrid economic optimal operation of the combined heat and power system with renewable energy. IEEE PES Gen Meet 2010:1–6.
[26] Vélez F, Segovia JJ, Martín MC, Antolín G, Chejne F, Quijano A. "A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renew Sustain Energy Rev 2012;16(6):4175–89.
[27] De Paepe M, Herdt PD, Mertens D. Micro-CHP systems for residential applications, 47; 2006. p. 3435–3446.
[28] Lee H, Bush J, Hwang Y, Radermacher R. Modeling of micro-CHP (combined heat and power) unit and evaluation of system performance in building application in United States. Energy 2013;58:364–75.
[29] Aoun B, Peuportier B. Experimental characterization, modeling and simulation of a wood pellet micro-combined heat and power unit used as a heat source for a residential building. Energy Build 2010;42:896–903.
[30] Hagi H, Neveux T, Le Y. Efficiency evaluation procedure of coal- fi red power plants with CO_2 capture, cogeneration and hybridization. Energy 2015;91:306–23.
[31] Gulhane SJ, Thakur Amit Kumar. Exergy analysis of boiler In cogeneration thermal power plant. Am J Eng Res 2013;2(10):385–92.
[32] Buoro D, Pinamonti P, Reini M. Optimization of a distributed cogeneration system with solar district heating. Appl Energy 2014;124:298–308.
[33] Biezma MV, Cristóbal JR San. Investment criteria for the selection of cogeneration plants - A state of the art review. Appl Therm Eng 2006;26(5–6):583–8.
[34] Hashemi R. A developed offline model for optimal operation of combined heating and cooling and power systems. IEEE Trans Energy Convers 2009;24(1):222–9.
[35] Twaha S, Ha M, Anwari M, Khairuddin A. Applying grid-connected photovoltaic system as alternative source of electricity to supplement hydro power instead of using diesel in Uganda, 37; 2012. p. 185–194.
[36] Moradi MH, Hajinazari M, Jamasb S, Paripour M. An energy management system (EMS) strategy for combined heat and power (CHP) systems based on a hybrid optimization method employing fuzzy programming. Energy 2013;49:86–101.
[37] Policy E, Cedex G, Investments R. Smart grids : Another step towards competition, energy security and climate change objectives, 39; 2011. p. 5399–5408.
[38] Kabalci E, Kabalci Y, Develi I. Electrical power and energy systems modelling and analysis of a power line communication system with QPSK modem for renewable smart grids. Int J Electr Power Energy Syst 2012;34(1):19–28.
[39] Güngör VC. et al. Smart grid technologies: communication technologies and standards, 7, 4; 2011. p. 529–539.
[40] Naumann A, Bielchev I, Voropai N, Styczynski Z. Smart grid automation using IEC 61850 and CIM standards. Control Eng Pract 2014;25:102–11.
[41] Becker DJ, Power EN, Systems E. Smart Grid.
[42] Depuru SSSR, Wang L, Devabhaktuni V. Smart meters for power grid: challenges, issues, advantages and status. Renew Sustain Energy Rev 2011;15(6):2736–42.
[43] HAmilton BA, Miller J, Renz B. Understanding the benefits of the smart grid: smart grid implementation strategy; 2010.
[44] The Smart Grid: An introduction.
[45] Attacking the smart grid, no. December; 2011.
[46] Colak I, Kabalci E, Fulli G, Lazarou S. A survey on the contributions of power electronics to smart grid systems. Renew Sustain Energy Rev 2015;47(1):562–79.
[47] Colak I, Sagiroglu S, Fulli G, Yesilbudak M. A survey on the critical issues in smart grid technologies. Renew Sustain Energy Rev 2016;54:396–405.
[48] Tan X, Li Q, Wang H. Advances and trends of energy storage technology in Microgrid. Int J Electr Power Energy Syst 2013;44(1):179–91.
[49] Lasseter RH. Smart distribution: coupled Microgrids. Proc IEEE 2011;99(6):1074–82.
[50] Jiayi H, Chuanwen J, Rong X. A review on distributed energy resources and MicroGrid. Renew Sustain Energy Rev 2008;12(9):2472–83.
[51] Subburaj AS, Pushpakaran BN, Bayne SB. Overview of grid connected renewable energy based battery projects in USA. Renew Sustain Energy Rev 2015;45:219–34.
[52] Zhu Y, Member S, Zhuo F, Shi H. Power Management Strategy Research for a Photovoltaic-Hybrid Energy Storage System, 2012; 2013. p. 842–848.
[53] Yang W, Xin A, Yang G, Microgrid's operation-management containing distributed generation system, *2011 4th International Conference Electr. Util. Deregul. Restruct. Power Technol*; Jul. 2011. p. 703–707.
[54] Qin Q, Chen Z, Wang X. Overview of micro-grid energy management system research status, *2012 Power Eng. Autom. Conference*; 2012, p. 1–4.
[55] Mahmoud MS, Azher Hussain S, Abido M a. Modeling and control of microgrid: an overview. J Frankl Inst 2014;351(5):2822–59.
[56] Zhang X, Member S, Sharma R, He Y. Optimal energy management of a rural microgrid system using multi-objective; 2011. p. 1–8.
[57] Basak P, Chowdhury S, Halder S, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev 2012;16(8):5545–56.
[58] Fu Q, Nasiri A, Solanki A, Bani-Ahmed A, Weber L, Bhavaraju V. Microgrids: architectures, controls, protection, and demonstration. Electr Power Compon Syst 2015;43(12):1453–65.
[59] Lidula NW a, Rajapakse aD. Microgrids research: a review of experimental microgrids and test systems. Renew Sustain Energy Rev 2011;15(1):186–202.
[60] Ustun TS, Ozansoy C, Zayegh A. Recent developments in microgrids and example cases around the world—A review. Renew Sustain Energy Rev 2011;15(8):4030–41.
[61] Abu-sharkh S. et al. Can microgrids make a major contribution to UK energy supply? 10; 2006. p. 78–127.
[62] Lasseter RH. MicroGrids, *2002 IEEE Power Eng. Soc. Winter Meet. Conference Proceedings (Cat.* No.02CH37309), 1; 2002. p. 305–308.
[63] Kumar A, Chowdhury SP, Chowdhury S, Paul S. Microgrids: energy management by strategic deployment of DERs — A comprehensive survey. Renew Sustain Energy Rev 2011;15(9):4348–56.
[64] Planas E, Gil-de-Muro A, Andreu J, Kortabarria I, Martínez de Alegría I. General aspects, hierarchical controls and droop methods in microgrids: a review. Renew Sustain Energy Rev 2013;17:147–59.
[65] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management—Part I: hierarchical control, energy storage, virtual power plants, and market participation. Renew Sustain Energy Rev 2014;36:428–39.
[66] Adamiak M, Baigent D, Mackiewicz R. IEC 61850 Communication networks and systems in substations: An overview for users; 2009.
[67] McMorran AW. An Introduction to IEC 61970-301 & 61968-11: The common information model; 2007.
[68] Vigen J, No O. IEC TR 62325-101; 2005.
[69] McNaughton GA, Robinson G, Gray GR. MultiSpeak and IEC 61968 CIM: moving towards interoperability. Forum Am. Bar Assoc, 155 2008; 2008. p. 1–6.
[70] IEEE standard for synchrophasor measurements for power systems, IEEE Power Energy Soc; 2011.
[71] Boyce MaherwanP, Handbook for cogeneration and combined cycle power plants..

[72] Siirola JJ, Edgar TF. Process energy systems: control, economic, and sustainability objectives. Comput Chem Eng 2012;47:134–44.
[73] David Flin. Cogeneration, a user's guide. Series 2010;11.
[74] Tsai WT, Hsien KJ. An analysis of cogeneration system utilized as sustainable energy in the industrial sector in Taiwan. Renew Sustain Energy Rev 2007;11(9):2104–20.
[75] Safaei A, Freire F, Antunes CH. A model for optimal energy planning of a commercial building integrating solar and cogeneration systems. Energy 2013;61:211–23.
[76] Arteconi A, Brandoni C, Polonara F. Distributed generation and trigeneration: energy saving opportunities in Italian supermarket sector. Appl Therm Eng 2009;29(8–9):1735–43.
[77] Wansheng Y. Analysis on energy saving for a Cool, Heat and Power Cogeneration System with a Micro Gas Turbine, 39000; 2010.
[78] Azit AH, Nor KM. Optimal sizing for a gas-fired grid-connected cogeneration system planning. IEEE Trans ENergy Convers 2009;24(4):950–8.
[79] Shaaban M, Azit aH, Nor KM. Grid integration policies of gas-fired cogeneration in Peninsular Malaysia: fallacies and counterexamples. Energy Policy 2011;39(9):5063–75.
[80] Somcharoenwattana W, Menke C, Kamolpus D, Gvozdenac D. Study of operational parameters improvement of natural-gas cogeneration plant in public buildings in Thailand. Energy Build . 2011;43(4):925–34.
[81] Park HSI, Hsu C. Cogeneration system design for a; 2002. p. 1733–1739.
[82] Chung M, Park H-C, Coimbra CFM. Estimation of the building energy loads and LNG demand for a cogeneration-based community energy system: a case study in Korea. Energy Convers Manag 2014;87:1010–26.
[83] Radulovic D, Skok S, Kirincic V. Cogeneration - Investment dilemma. Energy 2012;48(1):177–87.
[84] Kurata O, et al. Micro gas turbine cogeneration system with latent heat storage at the University: part I: plan and energy flow test. Appl Therm Eng 2014;65(1–2):513–23.
[85] Kurata O, et al. Micro gas turbine cogeneration system with latent heat storage at the University: part II: part load and thermal priority mode. Appl Therm Eng 2014;65(1–2):246–54.
[86] Kovac A. Electricity cogeneration in an exothermic reactor circuit system using an open gas turbine, 118; 2014. p. 220–226.
[87] Gimelli A, Muccillo M. Optimization criteria for cogeneration systems: multi-objective approach and application in an hospital facility. Appl Energy 2013;104:910–23.
[88] Marshman DJ, Chmelyk T, Sidhu MS, Gopaluni RB, Dumont G a. Energy optimization in a pulp and paper mill cogeneration facility. Appl Energy 2010;87(11):3514–25.
[89] Shnaiderman M, Keren N. Cogeneration versus natural gas steam boiler: a techno-economic model. Appl Energy 2014;131:128–38.
[90] Alanne K, Saari K, Kuosa M, Jokisalo J, Martin AR. Thermo-economic analysis of a micro-cogeneration system based on a rotary steam engine (RSE). Appl Therm Eng 2012;44:11–20.
[91] dos Santos RG, de Faria PR, Santos JJCS, da Silva JAM, Fl??rez-Orrego D. Thermoeconomic modeling for CO_2 allocation in steam and gas turbine cogeneration systems. Energy 2016;117:590–603.
[92] Kang DW, Jang HJ, Kim TS. Using compressor discharge air bypass to enhance power generation of a steam-injected gas turbine for combined heat and power. Energy 2014;76:390–9.
[93] Industrial applications for micropower: A market assessment; 1999.
[94] Daviot N, Bot P, Billard J, Ellis D, Podhorsky M, Brenner A. EDUCOGEN: The European Education Tool on Energy Efficiency through the use of cogeneration; 2000.
[95] Muccillo M, Gimelli A. Experimental development, 1D CFD simulation and energetic analysis of a 15 kw micro-CHP unit based on reciprocating internal combustion engine. Appl Therm Eng 2014;71(2):760–70.
[96] Lontsi F, Hamandjoda O, Fozao K, Stouffs P, Nganhou J. Dynamic simulation of a small modified Joule cycle reciprocating Ericsson engine for micro-cogeneration systems. Energy 2013;63:309–16.
[97] Yun KT, Cho H, Luck R, Mago PJ. Modeling of reciprocating internal combustion engines for power generation and heat recovery. Appl Energy 2013;102:327–35.
[98] Taleb AI, Timmer MAG, El-Shazly MY, Samoilov A, Kirillov VA, Markides CN. A single-reciprocating-piston two-phase thermofluidic prime-mover. Energy 2016;104:250–65.
[99] Kim Y, Kawahara N, Tsuboi K, Tomita E. Combustion characteristics and NO_X emissions of biogas fuels with various CO_2 contents in a micro co-generation spark-ignition engine. Appl Energy 2016;182(X):539–47.
[100] Valenti G, Silva P, Fergnani N, Di Marcoberardino G, Campanari S, Macchi E. Experimental and numerical study of a micro-cogeneration Stirling engine for residential applications. Energy Procedia 2014;45:1235–44.
[101] Outline C. Microturbines, fuel cells, and hybrid systems *; 2015. p. 835–859.
[102] Chapter 10 combined heat and power with microturbines. p. 91–120.
[103] Renewable N, Ridge O, Heinemann B. Chapter 2 Design and Components of Microturbines; 2007. p. 9–19.
[104] Zogg R, Bowman J, Roth K, Brodrick J. Using microturbines. ASHRAE J 2007;49.
[105] Majid MAA, Nasir M, Waluyo J. Operation and performance of a thermal energy storage system: a case study of campus cooling using cogeneration plant. Energy Procedia 2012;14:1280–5.
[106] Ismail MS, Moghavvemi M, Mahlia TMI. Current utilization of microturbines as a part of a hybrid system in distributed generation technology. Renew Sustain Energy Rev 2013;21:142–52.
[107] Meybodi MA, Behnia M. A study on the optimum arrangement of prime movers in small scale microturbine-based CHP systems. Appl Therm Eng 2012;48:122–35.
[108] Kalantar M, Mousavi G SM. Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. Appl Energy 2010;87(10):3051–64.
[109] Gaonkar DN, Patel RN. Modeling and Simulation of Microturbine Based Distributed Generation System, *2006 IEEE Power India Conference*; 2006, p. 0–4.
[110] Saha AK, Chowdhury S, Chowdhury SP. Modeling and simulation of microturbine, *2010 International Conference Power Syst. Technol. Technol. Innov. Mak. Power Grid Smarter, POWERCON2010*; 2010. p. 1–5.
[111] Arav B, Shulman R, Dooun V. Basic concepts for forcing of low-power micro turbine generators. Procedia Eng 2016;150:1384–90.
[112] Moghaddam AA, Seifi A, Niknam T, Alizadeh Pahlavani MR. "Multi-objective operation management of a renewable MG (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source. Energy 2011;36(11):6490–507.
[113] Montero Carrero M, De Paepe W, Magnusson J, Parente A, Bram S, Contino F. Experimental characterisation of a micro Humid Air Turbine: assessment of the thermodynamic performance. Appl Therm Eng 2017;118:796–806.
[114] Halliday J, Ruddell A, Powell J, Peters M. Fuel cells: providing heat and power in the urban environment fuel cells: providing heat and power in the urban environment. Fuel Cell 2005.
[115] Darrow K, Tidball R, Wang J, Hampson A. Catalog of CHP Technologies : Technology Characterization – Fuel Cells, U.S Environmental Protection Agency Combined Heat and Power Partnership, no. March; 2015.
[116] Sharaf OZ, Orhan MF. An overview of fuel cell technology: fundamentals and applications. Renew Sustain Energy Rev 2014;32:810–53.
[117] Payman A, Pierfederici S, Meibody-tabar F. Energy control of supercapacitor / fuel cell hybrid power source, vol. 49; 2008. p. 1637–1644.
[118] Dash V, Bajpai P. Power management control strategy for a stand-alone solar photovoltaic-fuel cell – battery hybrid system. Sustain Energy Technol Assess 2015;9:68–80.
[119] Stanton K, Lai JJ, Nelson D, Dynamic PEM fuel cell model for power electronics design with temperature consideration.
[120] Lagorse J, Paire D, Miraoui A. Sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery. Renew Energy 2009;34(3):683–91.
[121] Ham S, Jo S, Dong H, Jeong J. A simplified PEM fuel cell model for building cogeneration applications. Energy Build 2015;107:213–25.
[122] Thounthong P, Tricoli P, Davat B. Performance investigation of linear and nonlinear controls for a fuel cell/supercapacitor hybrid power plant. Int J Electr Power Energy Syst 2014;54:454–64.
[123] Shibata Y. Analysis on the cost effectiveness of the residential distributed energy system composed of fuel cell, Photovoltaics and Battery, no. August; 2012. p. 1–21.
[124] Isa NM, Das HS, Tan CW, Yatim AHM, Lau KY. A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital. Energy 2016;112:75–90.
[125] Wu W, Indah V, Chen S, Hwang J. Design and techno-economic optimization of a stand-alone PV (photovoltaic)/ FC (fuel cell)/ battery hybrid power system connected to a wastewater-to-hydrogen processor. Energy 2015;84:462–72.
[126] Han I, Park S, Chung C. Modeling and operation optimization of a proton exchange membrane fuel cell system for maximum efficiency. Energy Convers Manag 2016;113:52–65.
[127] Elmer T, Worall M, Wu S, Riffat SB. Fuel cell technology for domestic built environment applications: state of-the-art review. Renew Sustain Energy Rev 2015;42:913–31.
[128] Douglas T. Dynamic modelling and simulation of a solar-PV hybrid battery and hydrogen energy storage system. J Energy Storage 2016;7:104–14.
[129] Hosseinalizadeh R, Shakouri G H, Amalnick MS, Taghipour P. "Economic sizing of a hybrid (PV-WT-FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: case study of Iran. Renew Sustain Energy Rev 2016;54:139–50.
[130] Ural Z, Gencoglu MT. Design and simulation of a pem fuel cell system; 2010.
[131] Ural Z, Gencoglu MT. Mathematical models of PEM fuel cells, no. June; 2010. p. 27–30.
[132] El-Sharkh MY, Rahman a, Alam MS. Evolutionary programming-based methodology for economical output power from PEM fuel cell for micro-grid application. J Power Sources 2005;139(1–2):165–9.
[133] Ang SMC, Fraga ES, Brandon NP, Samsatli NJ, Brett DJL. Fuel cell systems optimisation – methods and strategies. Int J Hydrog Energy 2011;36(22):14678–703.
[134] Sharifi Asl SM, Rowshanzamir S, Eikani MH. Modelling and simulation of the steady-state and dynamic behaviour of a PEM fuel cell. Energy 2010;35(4):1633–46.
[135] Mahlia TMI, Chan PL. Life cycle cost analysis of fuel cell based cogeneration system for residential application in Malaysia. Renew Sustain Energy Rev 2011;15(1):416–26.
[136] Ullah KR, Akikur RK, Ping HW, Saidur R, Hajimolana S a, Hussain M a. An experimental investigation on a single tubular SOFC for renewable energy based cogeneration system. Energy Convers Manag 2015;94:139–49.
[137] Vural B, et al. Fuel cell and ultra-capacitor hybridization: a prototype test bench based analysis of different energy management strategies for vehicular applications. Int J Hydrog Energy 2010;35(20):11161–71.
[138] Bruni G, Cordiner S, Mulone V. Domestic distributed power generation: effect of sizing and energy management strategy on the environmental efficiency of a photovoltaic-battery-fuel cell system. Energy 2014;77:133–43.

[139] Thounthong P, Chunkag V, Sethakul P, Sikkabut S, Pierfederici S, Davat B. Energy management of fuel cell/solar cell/supercapacitor hybrid power source. J Power Sources 2011;196(1):313–24.
[140] Saravanan S, Thangavel S. Instantaneous reference current scheme based power management system for a solar/wind/fuel cell fed hybrid power supply. Int J Electr Power Energy Syst 2014;55:155–70.
[141] Hannan M a, Azidin F a, Mohamed a. Multi-sources model and control algorithm of an energy management system for light electric vehicles. Energy Convers Manag 2012;62:123–30.
[142] Lin W-S, Zheng C-H. Energy management of a fuel cell/ultracapacitor hybrid power system using an adaptive optimal-control method. J Power Sources 2011;196(6):3280–9.
[143] Abedi S, Alimardani A, Gharehpetian GB, Riahy GH, Hosseinian SH. A comprehensive method for optimal power management and design of hybrid RES-based autonomous energy systems. Renew Sustain Energy Rev 2012;16(3):1577–87.
[144] Rahimi S, Meratizaman M, Monadizadeh S, Amidpour M. Techno-economic analysis of wind turbine–PEM (polymer electrolyte membrane) fuel cell hybrid system in standalone area. Energy 2014;67:381–96.
[145] Abdullrahman , Addowash KE. Techno-economic optimization of hybrid power system using genetic algorithm. Int J Energy Res 2014;31:135–47.
[146] Napoli R, Gandiglio M, Lanzini A, Santarelli M. Techno-economic analysis of PEMFC and SOFC micro-CHP fuel cell systems for the residential sector. Energy Build 2015;103:131–46.
[147] Karakoulidis K, Mavridis K, Bandekas DV, Adoniadis P, Potolias C, Vordos N. Techno-economic analysis of a stand-alone hybrid photovoltaic-diesel e battery-fuel cell power system. Renew Energy 2011;36(8):2238–44.
[148] Pellegrino S, Lanzini A, Leone P. Techno-economic and policy requirements for the market-entry of the fuel cell micro-CHP system in the residential sector. Appl Energy 2015;143:370–82.
[149] Ren H, Wu Q, Gao W, Zhou W. Optimal operation of a grid-connected hybrid PV / fuel cell / battery energy system for residential applications. Energy 2016;113:702–12.
[150] Buonomano A, Calise F, Dentice M, Palombo A, Vicidomini M. Hybrid solid oxide fuel cells – gas turbine systems for combined heat and power: a review. Appl Energy 2015;156:32–85.
[151] Selwynraj AI, Iniyan S, Polonsky G, Suganthi L, Kribus A. Exergy analysis and annual exergetic performance evaluation of solar hybrid STIG (steam injected gas turbine) cycle for Indian conditions. Energy 2015;80:414–27.
[152] Mundada AS, Shah KK, Pearce JM. Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. Renew Sustain Energy Rev 2016;57:692–703.
[153] Roy K, Mandal KK, Mandal AC. Modeling and managing of micro grid connected system using Improved Artificial Bee Colony algorithm. Int J Electr Power Energy Syst 2016;75:50–8.
[154] Kalina J. Integrated biomass gasification combined cycle distributed generation plant with reciprocating gas engine and ORC. Appl Therm Eng 2011;31(14–15):2829–40.
[155] Obara S, Morel Rios JR, Okada M. Control of cyclic fluctuations in solid oxide fuel cell cogeneration accompanied by photovoltaics. Energy 2015;91:994–1008.
[156] Ferreira AC, Nunes ML, Teixeira JCF, Martins LASB, Teixeira SFCF. Thermodynamic and economic optimization of a solar-powered Stirling engine for micro-cogeneration purposes. Energy 2016;111:1–17.
[157] Balcombe P, Rigby D, Azapagic A. Environmental impacts of microgeneration: integrating solar PV, Stirling engine CHP and battery storage. Appl Energy 2015;139:245–59.
[158] Balcombe P, Rigby D, Azapagic A. Energy self-sufficiency, grid demand variability and consumer costs: integrating solar PV, Stirling engine CHP and battery storage. Appl Energy 2015;155:393–408.
[159] Pedrazzi S, Zini G, Tartarini P. Modelling and simulation of a wind-hydrogen CHP system with metal hydride storage. Renew Energy 2012;46:14–22.
[160] Prinsloo G, Mammoli A, Dobson R. Discrete cogeneration optimization with storage capacity decision support for dynamic hybrid solar combined heat and power systems in isolated rural villages. Energy 2016;116:1051–64.
[161] Meng L, Riva E, Luna A, Dragicevic T, Vasquez JC, Guerrero JM. Microgrid supervisory controllers and energy management systems: a literature review. Renew Sustain Energy Rev 2016;60:1263–73.
[162] Bouzid AM, Guerrero JM, Cheriti A, Bouhamida M, Sicard P, Benghanem M. A survey on control of electric power distributed generation systems for microgrid applications. Renew Sustain Energy Rev 2015;44:751–66.
[163] Zeng Z, Yang H, Zhao R, Cheng C. Topologies and control strategies of multi-functional grid-connected inverters for power quality enhancement: a comprehensive review. Renew Sustain Energy Rev 2013;24:223–70.
[164] Hirech K, Melhaoui M, Yaden F, Baghaz E, Kassmi K. Design and realization of an autonomous system equipped with a charge / discharge regulator and digital MPPT command. Energy Procedia 2013;42:503–12.
[165] Eltawil MA, Zhao Z. MPPT techniques for photovoltaic applications. Renew Sustain Energy Rev 2013;25:793–813.
[166] Hong C-M, Ou T-C, Lu K-H. Development of intelligent MPPT (maximum power point tracking) control for a grid-connected hybrid power generation system. Energy 2013;50:270–9.
[167] Tan CW, Green TC, Hernandez-aramburo CA, A current-mode controlled maximum power point tracking converter for building integrated photovoltaics acknowledgment keywords characteristic of photovoltaic generation BP 365U at standard test condition.
[168] Tan CW, Green TC, Member S, Hernandez-aramburo CA. An improved maximum power point tracking algorithm with current-mode control for photovoltaic applications, 1; 2005. p. 489–494.
[169] Vasquez-arnez RL, Soares D, Elena T, Carpio-huayllas D. Electrical power and energy systems Microgrid dynamic response during the pre-planned and forced islanding processes involving DFIG and synchronous generators. Int J Electr Power Energy Syst 2014;62:175–82.
[170] Zamora R, Srivastava AK. Controls for microgrids with storage: review, challenges, and research needs. Renew Sustain Energy Rev 2010;14(7):2009–18.
[171] Dimeas AL, Member S, Hatziargyriou ND, Member S. Operation of a multiagent system for microgrid control, 20, 3; 2005. p. 1447–1455.
[172] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrid management: controls and operation aspects of microgrids. IEEE Power Energy Mag 2008:54–65.
[173] Dimeas AL, Ieee SM, Hatziargyriou ND, Member S. A MAS architecture for Microgrids control; 2005. p. 402–406.
[174] Chauhan A, Saini RP. A review on integrated renewable energy system based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. Renew Sustain Energy Rev 2014;38:99–120.
[175] Tarasantisuk C, Chunkag V, Thounthong P. Control of parallel-connected AC to DC converter with droop technique for DC microgrid application. Energy Procedia 2013;34:351–61.
[176] Bidram A, Member S, Davoudi A. Hierarchical structure of microgrids control system, 3, 4; 2012. p. 1963–1976.
[177] Tsikalakis AG, Member S, Hatziargyriou ND, Member S, Microgrids A. Centralized control for optimizing microgrids operation, 23, 1; 2008. p. 241–248.
[178] Scherer HF, Pasamontes M, Guzmán JL, Álvarez JD, Camponogara E, Normey-Rico JE. Efficient building energy management using distributed model predictive control. J Process Control 2014;24(6):740–9.
[179] Cagnano A, Tuglie E De. Centralized voltage control for distribution networks with embedded PV systems. Renew Energy 2015;76:173–85.
[180] Ebrahimi FM, Khayatiyan A, Farjah E. A novel optimizing power control strategy for centralized wind farm control system. Renew Energy 2016;86:399–408.
[181] Chen D, Xu L. Autonomous DC voltage control of a DC microgrid with multiple slack terminals. IEEE Trans Power Syst 2012;27(4):1897–905.
[182] Arul PG, Ramachandaramurthy VK, Rajkumar RK. Control strategies for a hybrid renewable energy system: a review. Renew Sustain Energy Rev 2015;42:597–608.
[183] Su W, Wang J. Energy management systems in microgrid operations. Electr J 2012;25(8).
[184] Ye L, Bo H, Ri X, Cheng L. Dynamic modeling of a hybrid wind / solar / hydro microgrid in EMTP / ATP. Renew Energy 2012;39(1):96–106.
[185] Strunz K, Abbasi E, Huu DN. DC Microgrid for wind and solar power integration, 2, 1; 2014. p. 115–126.
[186] Gu Y, Xiang X, Li W, He X. Mode-adaptive decentralized control for renewable DC microgrid with enhanced reliability and, 29, 9; 2014. p. 5072–5080.
[187] Kantamneni A, Brown LE, Parker G, Weaver WW. Engineering applications of artificial intelligence survey of multi-agent systems for microgrid control. Eng Appl Artif Intell 2015;45:192–203.
[188] Dimeas A, Hatziargyriou N, Member S, A Multi agent system for microgrids; p. 1–4.
[189] Smitha SD. Intelligent energy management in smart and sustainable buildings with multi-agent control system; 2013. p. 190–195.
[190] Jia X, Dou C. Application of multi-agent technology in micro-grid system, in *2011 The International Conference on Advanced Power System Automation and Protection*, 8, 10; 2011. p. 35–48.
[191] Dou C-X, Yue D, Guerrero J. Multi-agent system based event-triggered hybrid controls for high-security hybrid energy generation systems. IEEE Trans Ind Inform 2016:1, [pp. 1–1].
[192] Dimeas AL, Ieee M, Hatziargyriou ND, Member S. Multi-agent reinforcement learning for microgrids; 2010. p. 1–8.
[193] Mokhtar M, Liu X, Howe J. Multi-agent Gaussian Adaptive Resonance Theory Map for building energy control and thermal comfort management of UCLan's WestLakes Samuel Lindow Building. Energy Build 2014;80:504–16.
[194] Rixen M, Weigand J. Agent-based simulation of policy induced diffusion of Smart meters. Technol Forecast Soc Change 2013.
[195] García P, García CA, Fernández LM, Llorens F, Jurado F. ANFIS-Based control of a grid-connected hybrid system integrating renewable energies, hydrogen and batteries. IEEE Trans Ind Inform 2014;10(2):1107–17.
[196] Wu X. et al. Data-driven predictive control of micro gas turbine combined cooling data-driven predictive control of micro gas turbine combined cooling data-driven predictive heating control and of micro system heating and power system heating and power system, IFAC-PapersOnLine, 49, 27; 2016. p. 419–424.
[197] Wiese AP, Blom MJ, Manzie C, Brear MJ, Kitchener A. Control engineering practice model reduction and MIMO model predictive control of gas turbine systems. Control Eng Pract 2015;45:194–206.
[198] De Pascale A, Semprini S, Sa D. Performance analysis of a micro gas turbine and solar dish integrated system under different solar-only and hybrid operating conditions. Sol Energy 2016;132:279–93.
[199] Kohsri S, Plangklang B. Energy management and control system for smart renewable energy remote power generation. Energy Procedia . 2011;9(2):198–206.
[200] Bernard F, Kolanowski . Small scale cogeneration handbook. The Fairmont Press; 2000.
[201] Madlener R, Schmid C. Combined heat and power generation in liberalised markets and a carbon-constrained world. Sustain Energy Provis 2003.
[202] Nyboer J, Groves S. A review of existing cogeneration facilities in Canada; 2012.
[203] de Rubeis T, et al. Multi-year consumption analysis and innovative energy perspectives: the case study of Leonardo da Vinci International Airport of Rome.

Energy Convers Manag 2016;128:261–72.
[204] Italian Civil Aviation Authority. [Online]. Available: ⟨https://www.enac.gov.it/servizio/info_in_english/⟩. [Accessed 11 January 2017].
[205] Kilkiş B. Energy consumption and CO_2 emission responsibilities of terminal buildings: a case study for the future Istanbul International Airport. Energy Build 2014;76:109–18.
[206] Cardona E, Piacentino A, Cardona F. Energy saving in airports by trigeneration. Part I: assessing economic and technical potential. Appl Therm Eng 2006;26(14–15):1427–36.
[207] Cardona E, Sannino P, Piacentino A, Cardona F. Energy saving in airports by trigeneration. Part II: short and long term planning for the Malpensa 2000 CHCP plant. Appl Therm Eng 2006;26(14–15):1437–47.
[208] Hospital E, Alliance E, Hospitals realize greatest savings through formal energy management program.
[209] Paper W. et al. Cogeneration for hospitals, 760; 1978. p. 1870–1872.
[210] Silveira JL, Lamas WDQ, Tuna CE, Villela IADC, Miro LS. Ecological efficiency and thermoeconomic analysis of a cogeneration system at a hospital. Renew Sustain Energy Rev 2012;16(5):2894–906.
[211] Damberger T a. Fuel cells for hospitals. J Power Sources 1998;71(1–2):45–50.
[212] Kowloon Hospital Solar-Wind Turbine Hybrid System, Hong Kong, Jardine Engineering Corporation; 2008. p. 310.
[213] North Country hospital biomass combined heat and power demonstration project; 2007.
[214] Renedo CJ, Ortiz a, Mañana M, Silió D, Pérez S. Study of different cogeneration alternatives for a Spanish hospital center. Energy Build 2006;38(5):484–90.
[215] Renedo CJ, Ortiz A, Silió D, Mañana M, Pérez S, Carcedo J, Cogeneration in a Hospital: a case study.
[216] Alexis GK, Liakos P. A case study of a cogeneration system for a hospital in Greece. economic and environmental impacts. Appl Therm Eng 2013;54(2):488–96.
[217] Costa A, Fichera A. A mixed-integer linear programming (MILP) model for the evaluation of CHP system in the context of hospital structures. Appl Therm Eng 2014;71(2):921–9.
[218] Meng J, Chen P, Ni M. Economic analysis of a solid oxide fuel cell cogeneration / trigeneration system for hotels in Hong Kong. Energy Build 2014;75:160–9.
[219] Galvão JR, Leitão SA, Silva SM, Gaio TM. Cogeneration supply by bio-energy for a sustainable hotel building management system. Fuel Process Technol 2011;92(2):284–9.
[220] Dalton GJ, Lockington DA, Baldock TE. Feasibility analysis of renewable energy supply options for a grid-connected large hotel. Renew Energy 2009;34(4):955–64.
[221] Shelar M, Kulkarni GN. Thermodynamic and economic analysis of diesel engine based trigeneration systems for an Indian hotel. Sustain Energy Technol Assess 2016;13:60–7.
[222] Khani L, Mahmoudi SMS, Chitsaz A, Rosen MA. Energy and exergoeconomic evaluation of a new power/cooling cogeneration system based on a solid oxide fuel cell. Energy 2016;94:64–77.
[223] Romero Rodríguez L, Salmerón Lissén JM, Sánchez Ramos J, Rodríguez Jara EÁ, Álvarez Domínguez S. Analysis of the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/PV/micro-CHP systems. Appl Energy 2016;165:828–38.
[224] Akikur RK, Saidur R, Ping HW, Ullah KR. Performance analysis of a co-generation system using solar energy and SOFC technology. Energy Convers Manag 2014;79:415–30.
[225] Seo H, Sung J, Oh SD, suk Oh H, Kwak HY. Economic optimization of a cogeneration system for apartment houses in Korea. Energy Build 2008;40(6):961–7.
[226] Dentice d'Accadia M, Sasso M, Sibilio S, Vanoli L. Micro-combined heat and power in residential and light commercial applications. Appl Therm Eng 2003;23(10):1247–59.
[227] Brahman F, Honarmand M, Jadid S. Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. Energy Build 2015;90:65–75.
[228] Rosato A, Sibilio S, Ciampi G. Dynamic performance assessment of a building-integrated cogeneration system for an Italian residential application. Energy Build 2013;64:343–58.
[229] Braslavsky JH, Wall JR, Reedman LJ. Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre. Appl Energy 2015;155:120–30.
[230] Beatriz A, De Sousa L, Ramos REB, Factors Affecting the natural gas adoption in shopping mall in Brazil, in *IEE Proceedings Generation, Transmission & Distribution*.
[231] Tolmasquim MT, Szklo AS, Soares JB. Economic potential of natural gas fired cogeneration plants at malls in Rio de Janeiro. Energy Convers Manag 2001;42.